

PB-220 728

A Study of Mandatory Engine Maintenance for Reducing Vehicle Exhaust Emissions

Vol. 3

**a documentation handbook for the
economic effectiveness model
TRW Systems Group**

**prepared for
Environmental Protection Agency**

JULY 1972

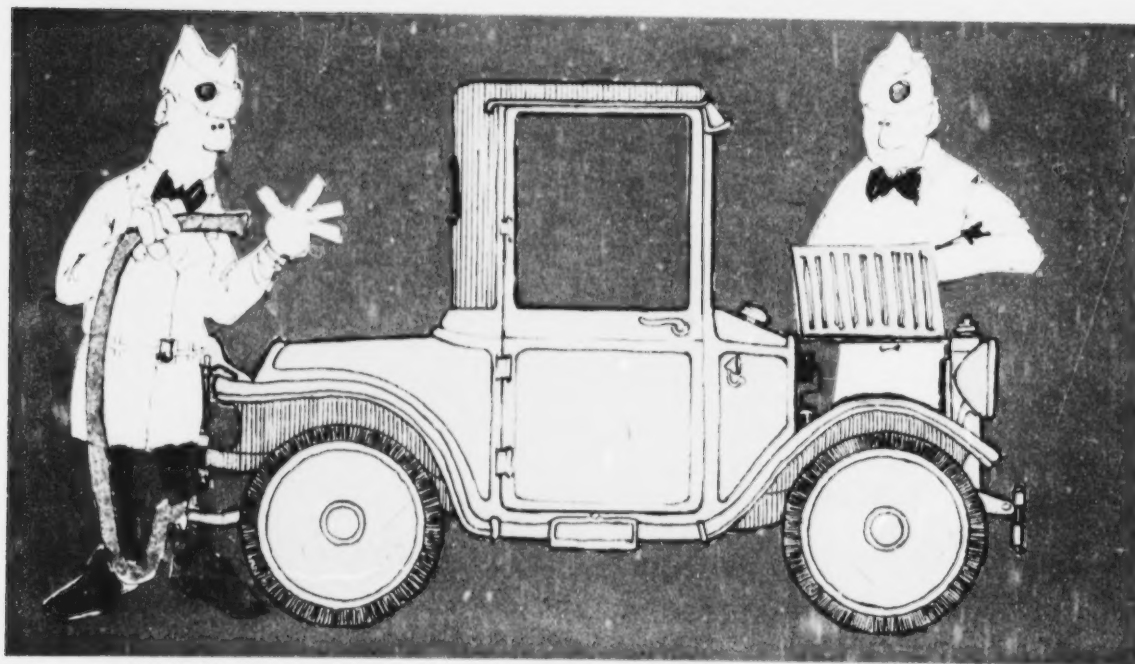
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A Study of PB 220 728 Mandatory Engine Maintenance for Reducing Vehicle Exhaust Emissions

Volume III. A Documentation Handbook for
the Economic Effectiveness Model



Year End Report
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PREFACE

This report, "A Study of Mandatory Engine Maintenance for Reducing Vehicle Exhaust Emissions," consists of six volumes. The following are the subtitles given for each volume:

- Executive Summary, Volume I
- Mandatory Inspection/Maintenance Systems Study, Volume II
- A Documentation Handbook for the Economic Effectiveness Model, Volume III
- Experimental Characterization of Vehicle Emissions and Maintenance States, Volume IV
- Experimental Characterization of Service Organization Maintenance Performance, Volume V
- A Comparison of Oxides of Nitrogen Measurements Made With Chemiluminescent and Non-Dispersive Radiation Analyzers, Volume VI

The first volume summarizes the general objectives, approach and results of the study. The second volume presents the results of the mandatory inspection/maintenance system study conducted with a computerized system model which is described in Volume III. The experimental programs conducted to develop input data for the model are described in Volume IV (Interim Report of 1971-72 Test Effort) and V. Volume VI presents comparative measurements of NO and NO_x using chemiluminescence and NDIR/NDUV instruments and differences in these measurements are examined.

The work presented herein is the product of a joint effort by TRW Systems Group and its subcontractor, Scott Research Laboratories. TRW, as the prime contractor, was responsible for overall program management, experimental design, data management and analysis, and the economic effectiveness study. Scott acquired and tested all of the study vehicles. Scott also provided technical assistance in selecting emission test procedures and in evaluating the test results.

ECONOMIC EFFECTIVENESS MODEL DOCUMENTATION

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1.0 INTRODUCTION

1.1 PURPOSE

The primary purpose of the Economic Effectiveness Model is to serve as a research and design tool for assessing the various implications of a mandatory program of vehicle inspection/maintenance. As such, it has been constructed with the capability to evaluate a wide range of possible procedure and design alternatives. The model is designed to both analyze the regional feasibility of vehicle inspection/maintenance as well as to specify an optimal system design. Input data for several regional areas covering the gamut of auto related air quality problems are incorporated into the model.

In addition to these functions, the model can also be used to analyze the sensitivity of system performance to various model assumptions and basic data inputs. Used in this way the model serves as a "self regulating device" for identifying areas requiring further analytical and empirical definition. The model by its very nature is policy oriented. That is, it is best used for evaluating the attractiveness of alternative policies, e.g., engine inspection or emission inspection, which govern and control the operation of an inspection/maintenance system. Actually, there exists a hierarchy of policy decision variables within the structure of the model. The determination of the optimal values for these variables is presently accomplished through the use of a para-optimization technique.

The main function of the model, in addition to analyzing policy variables, is in simulating the behavior of the inspection/maintenance process over time. Here, the economic-effectiveness of various strategies can be measured in terms of emission reductions and program costs at each time interval. A statistical analysis of these reductions can be undertaken as a further check on predicted model performance. The final step in this process is to utilize the unadjusted or statistically adjusted figure of merit for selecting the optimal model design for each candidate region.

1.2 BACKGROUND

A mandatory program of vehicle inspection/maintenance represents one short term approach for controlling exhaust emissions from automobiles. Such a program has the advantage of effecting most vehicles within the population fleet. The underlying principle governing the operation of an inspection/maintenance program is as follows:

"Reductions in a vehicle's exhaust emissions can be achieved through the adjustment and/or replacement of a specific set of engine block components."

Obviously, there exists a number of fundamental questions concerning the feasibility of a mandatory program. Among the more important ones are:

- (1) What is the range of expected emission reductions achievable from the various maintenance treatments?
- (2) What are the costs associated with each of these programs?
- (3) What is the impact of regional variations on overall program effectiveness and procedure selection?
- (4) How is program effectiveness likely to change with time and new control technology?

The development of the economic-effectiveness computer program represents an attempt to answer these questions. It provides a flexible tool for examining in an accurate and detailed manner the various alternatives which form the underpinnings of this control concept.

Automotive emission control through a program of inspection/maintenance can be accomplished by employing any one of a number of available options. However, there are in the limit two classes of inspection procedures which embody the entire range of possible alternatives. They are:

- o Direct measurement of the state of selected engine block components using conventional or more sophisticated garage-type equipment.
- o Indirect measurement of the state of selected engine block components using engine exhaust emission levels (signatures) under varying load conditions.

Each basic alternative has a number of distinct advantages and disadvantages. In the case of the direct approach, the chief benefit is in its ability to maximize potential emission reductions. Here, engine block components are adjusted and/or replaced based on a direct diagnosis of the engine state. The margin for error, in terms of omissions and commissions, is relatively small. The main disadvantage lies with the higher operating costs required for such a program. This type of program would normally be conducted in a franchised or certified, privately owned garage.

The indirect or emission inspection approach is more sophisticated in terms of both procedure techniques and equipment specifications. Hydrocarbon, carbon monoxide and NO_x emission measurements are made at several engine loadings. An analysis of these "mode" emission levels leads to the identification of faulty engine components. Although the costs for such a program are generally lower than for the direct approach, the resultant emission reductions are also smaller. This is due primarily to the higher incidence of inspection errors encountered in actual operation. The inspection portion of this approach is best performed in a state operated facility, whereas the maintenance treatment should be undertaken in a conventional franchised garage.

Embodied within each of these basic alternatives is an endless number of sub-strategies and system variations. Selection of the optimal policy set, therefore, entails a systematic tradeoff of the relevant program variables. One function of the model is to evaluate analytically the tradeoff implications of various variable sets. The following section presents a simplified overview on the structure and process of a vehicle inspection/maintenance program.

1.3 CONCEPTUAL FRAMEWORK AND PROCESS

A mandatory program of vehicle inspection maintenance can be viewed as a process with a fixed number of specific steps. The first step involves the inspection, either direct or indirect, of all vehicles within a given population. The inspection procedure is based on measuring the state of the engine, e.g., engine components and emission levels, and comparing these results with some prescribed criteria. If the measured value falls outside the allowable range, then the vehicle must undergo a specified maintenance treatment. Those vehicles passing the test are free to go without further involvement in the process. This cycle is repeated on a periodic basis over the time horizon of the program. Because of engine system deterioration, most vehicles will eventually undergo some form of maintenance treatment.

Figure 1-1 presents a schematic overview of the inspection/maintenance process for an emission inspection approach. Between inspection intervals a vehicle's exhaust emissions will normally rise due to the deterioration and/or malfunction of various engine block components. Thus, vehicles passing the initial test may in fact fail subsequent inspections. The converse is the case for many automobiles which failed the initial examination. Undergoing a selected maintenance treatment, the average vehicle should pass the next test assuming the criteria has remained invariant.

The conceptual structure of a vehicle inspection/maintenance program consists of three fundamental components:

- o Engineering Design
- o Economic Factors
- o Regional Data

Their interaction must be clearly understood in order to select the system design elements which yield optimal performance and cost. The factors of engineering design fall into two basic categories: (1) type of inspection/maintenance procedure and (2) facilities configuration. The cost of each candidate system must be computed in order to arrive at the program's overall effectiveness. The relevant costs here are composed of capital,

VEHICLE INSPECTION MAINTENANCE PROCESS

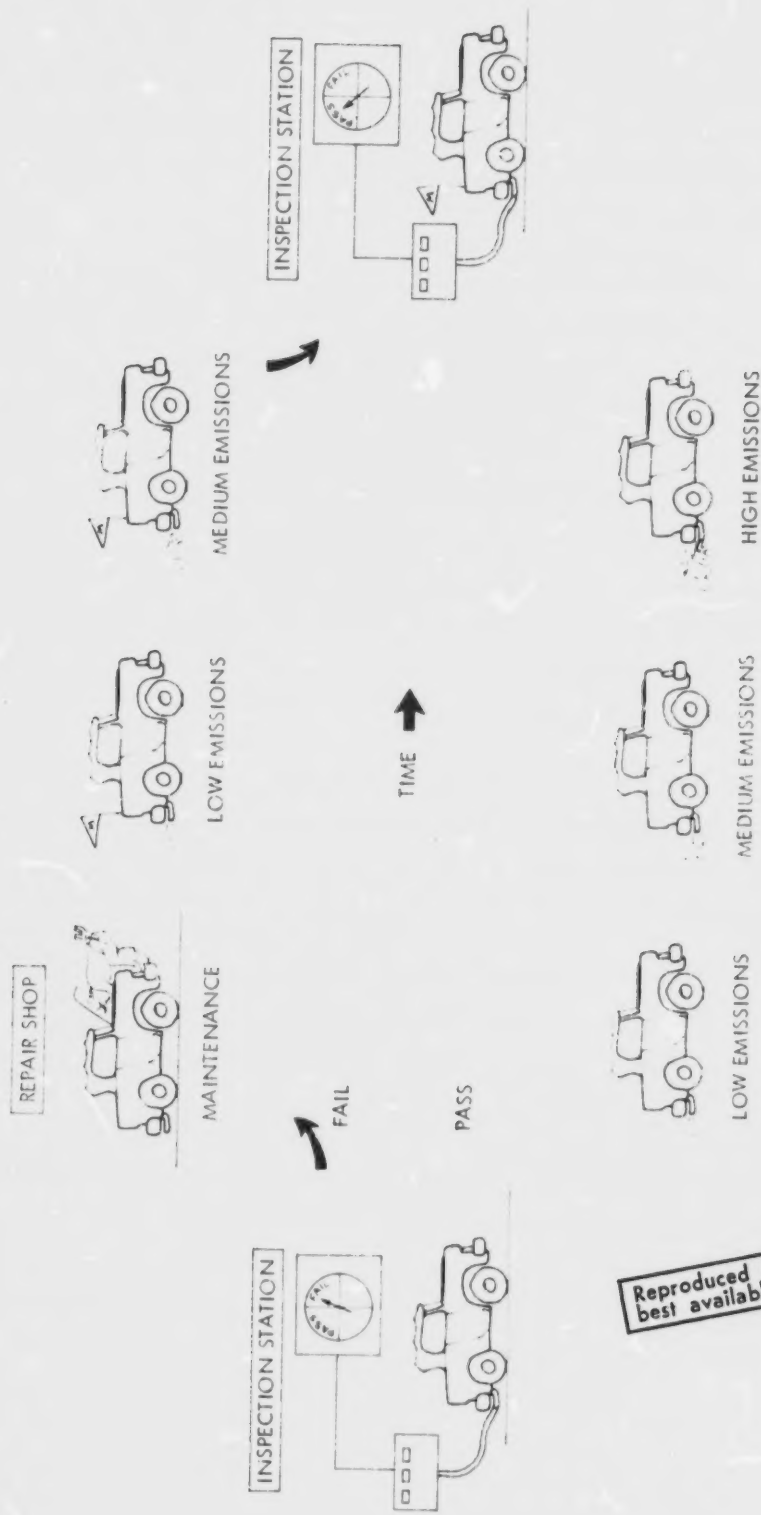


FIGURE 1-1 VEHICLE INSPECTION MAINTENANCE PROCESS

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labor and user inconvenience. Regional constraints take the form of air quality standards, minimum acceptable emission reductions, and maximum cost expenditures. Any viable program of inspection/maintenance should fall within these stated limits.

While emission reduction performance provides some insight into the feasibility of vehicle inspection/maintenance with respect to other control concepts, some function of both performance and costs is required in selecting the optimal system design. Unfortunately, no one function, i.e., figure of merit, appears to embody all of the characteristics desired in selecting from between the several alternatives. The most relevant figure of merit and the one incorporated in the Economic Effectiveness model consists of discounted total program cost divided by the weighted species emission reductions achieved over the time horizon of the program. Alternatively, the emission reductions at some future point in time may also be selected for calculating the figure of merit.

In addition to procedure selection, this figure of merit can also be used for determining the optimal values of the policy variables which unite the various elements of the system. A partial list of these variables is given below:

- Interval between inspections
- Pass/fail inspection criteria
- Extent of maintenance treatment
- Facilities configuration

To better understand the behavior of an inspection/maintenance system over time required the development of a mathematical computer model. Given in the next two sections is a discussion of analytical approach taken in designing the model and in constructing the Economic Effectiveness Computer Program.

1.4 METHODOLOGICAL APPROACH

The methodological approach adopted for constructing the Economic Effectiveness model involved a blending of theoretical and empirical relationships. The theory provided the conceptual framework for describing the inspection/maintenance process whereas the experimental data yielded the specific transformations needed to define and interconnect the various model elements.

The development of the model required a detailed specification of the various relationships characterizing the Inspection/Maintenance Process. Figure 1-2 shows schematically the salient components constituting the present model. The three main components -- engineering design, economic analysis and regional characterization form the core or nucleus of the inspection/maintenance model. Each of these components describes or delineates one fundamental aspect of the total process. How these interact must be clearly understood so that system design factors are selected in combinations to yield optimal cost and performance.

Attempting to describe a physical process with an abstract mathematical model raises a number of technical problems. One important issue involves the level of aggregation used in the model to characterize the actual process. Use of a simulation model yields an effective vehicle for coping with many of these questions. Here, basic study grounds and model assumptions, e.g., level of aggregation, can be isolated and examined in detail. As such, a simulation model strikes a good balance between a strictly theoretical model and an empirical model. The simulation model used in describing the inspection/maintenance process provides a powerful tool not only for assessing the feasibility of this control approach but also in developing an optimal system design specification. One phase of such a feasibility assessment involves the evaluation of potential procedure strategies, e.g., engine inspection. Within this context, the simulation model can be used to measure the performance of these strategies over time and under varying system constraints. The resultant model design provides a great deal of flexibility yet contains sufficient depth to describe the process in intimate detail.

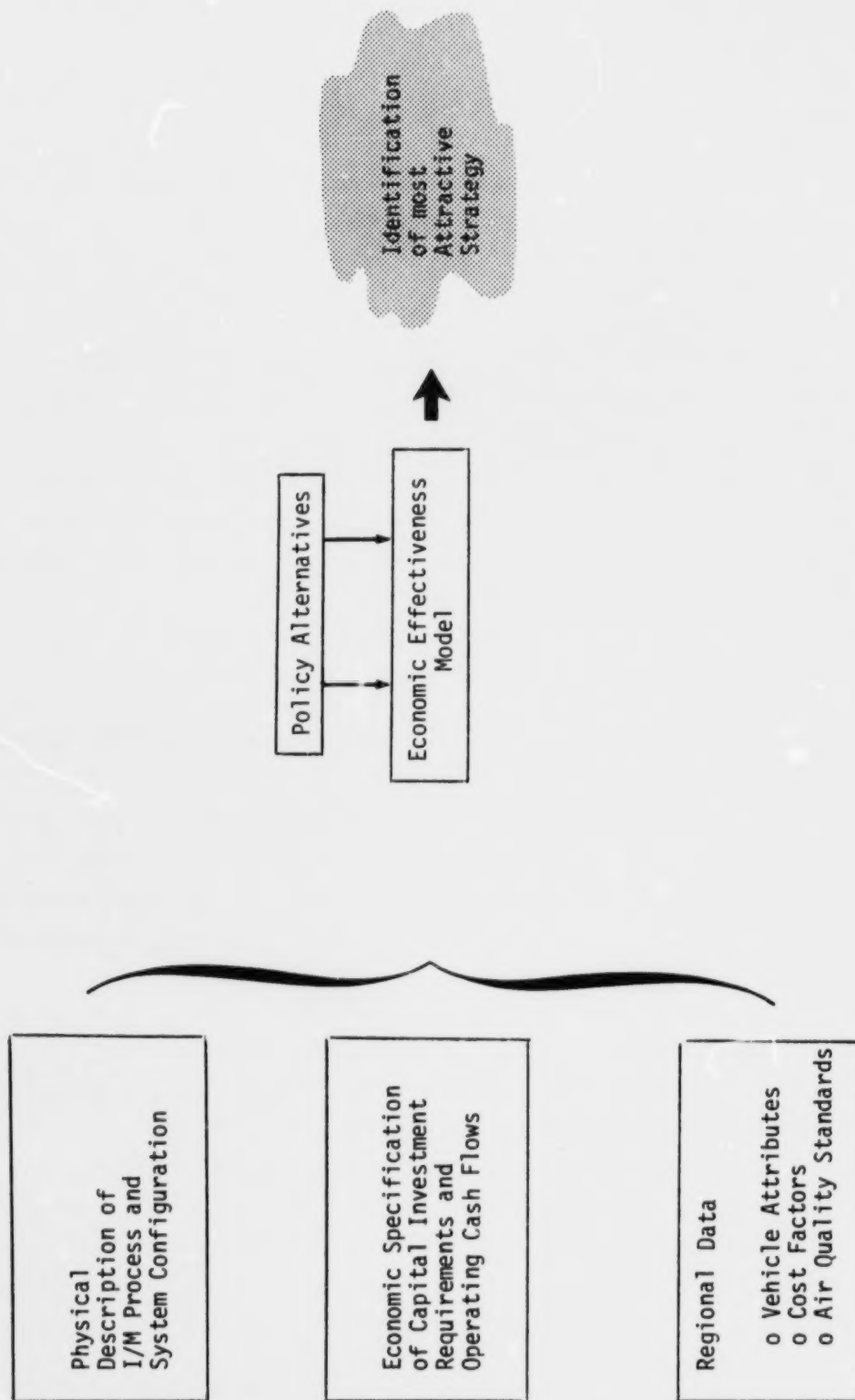


FIGURE 1-2 MODEL DESIGN OVERVIEW

1.5 COMPUTER PROGRAM DESIGN

The development of a conceptual model represented only part of this research effort. A second and equally important step involved the selection of a method for operationalizing the Economic Effectiveness Model. A computer-based design approach provided the flexibility needed to accommodate the large data bank and to evaluate the multiplicity of system tradeoffs.

The Economic Effectiveness Program has been coded in Fortran IV and is presently operating on a CDC 6500 system. Due to its flexible design, it can evaluate a wide range of potential strategies with little or no change to the basic model structure or data bank. Simplicity and flexibility are salient characteristics of the input language. The hub of this input system is its "key word" translator. It is used to convert literal phrases, e.g., idle or control fleet, into internal programming code. As such, it greatly reduces the time required to setup a computer run. An executive routine has also been added to check for input errors and to control output.

The program also provides several levels of output depending on user requirements. For standard cases, it outputs computer generated plots of emission time histories, program figure of merit, emission reductions and numerous accounting figures. For more detail information, a debug option is available which prints the basic calculations from each of the major subroutines. Figure 1-3 presents a schematic overview of the current program.

The primary use of the program is in simulating the performance of proposed inspection/maintenance procedures over a given time horizon. The program can also be used to develop an optimal system design for both a franchised garage and state-operated inspection station. Finally, the program provides means for testing the significance of various types of emissions data, and for measuring the impact of basic study ground rules.

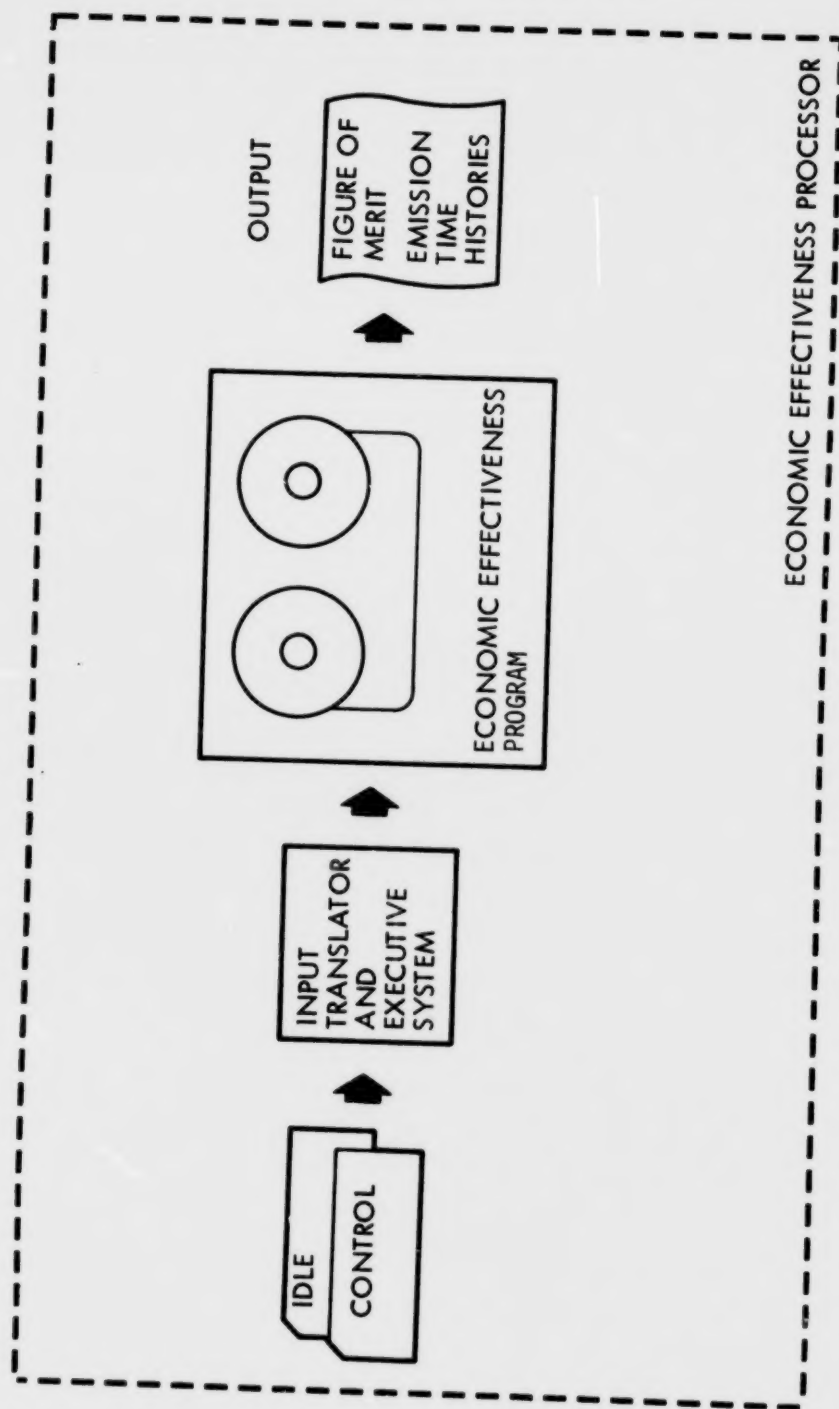


FIGURE 1-3 ECONOMIC EFFECTIVENESS PROCESSOR

2.0 PROGRAM SPECIFICATION

A mandatory program of vehicle inspection/maintenance embodies an endless number of possible system alternatives. These options run the gambit from policy decisions to instrumentation selection. This decision hierarchy introduces a great deal of complexity into the basic evaluation process. Such structural complexity becomes necessary, however, in order to achieve a reasonable degree of precision in predicted outcomes.

The two fundamental aspects of developing a viable program specification involve both procedure identification and system design. The first one focuses on the evaluation of various policy alternatives in terms of cost and effectiveness. The second is concerned with the overall relationships and interactions between the numerous components constituting the system. Both of these aspects are detailed in great degree within the Economic Effectiveness Model. Each one can be examined individually or simultaneously depending on the particular application.

2.1 POLICY EVALUATION

The problem of ultimate concern is the use of the Economic Effectiveness model in developing an optimal program of vehicle Inspection/Maintenance. This necessitates identification of all viable strategy options and their systematic examination via the model. The basic policy options available for examination in a program of vehicle inspection/maintenance are procedure selection and method of operation (state lane or franchise garage). Determination of the "best" procedure affords some insight into the feasibility of this approach for reducing exhaust emissions. Design of the optimal inspection/maintenance system will depend heavily on the cost attractiveness of the method of operation. Each of these options involves a number of potential variations. Selection of the optimal policy set, therefore, entails a systematic tradeoff analysis of all relevant variables and parameters. A quantitative measure of the effectiveness of these policies can be obtained by employing the systems framework embodied in the model.

2.1.1 Inspection Strategies

Two basic inspection strategies are available within the context of this control approach. These strategies must be both effective (result in substantial emission reductions) and economical to implement (lowest cost for the emission reductions achieved). A strategy as used here implies a policy statement concerning (1) whether inspection facilities are to be privately or publicly financed and operated; (2) what the quantitative inspection criteria are; (3) the type of mandatory maintenance to be performed in order to achieve the desired reductions in each of the emission species.

State vs. Private Inspection

A number of inspection/maintenance procedures have been suggested by other investigators. One of the purposes of the Economic-Effectiveness study is to evaluate the efficacy of these procedures and to rank them within a systematic framework. Methods of improving these procedures and/or identifying new ones may then proceed. Basic inspection approaches may generally be classified as to whether they are best applied in a state inspection lane or in a franchised garage. The state inspections generally imply a high process throughput and, therefore, sophisticated diagnostic instrumentation and data management systems with large capital expenditures. Typical of this strategy are approaches wherein several engine attributes are measured which are known to be highly correlated to engine maintenance state. The measurement of exhaust emissions under engine operating modes or truncated driving cycles typify this approach.

At the other end of the spectrum are those inspection approaches which use conventional or upgraded diagnostic equipment to identify engine malfunctions known to adversely influence exhaust emissions. These approaches tend to be labor intensive rather than capital intensive and are, therefore, more effectively applied in existing service organizations where trained labor and commercial equipment are already available. These are intermediate and special cases of interest, some of which may be studied within the currently structured computer model.

In order to select quantitative inspection criteria, the procedures for inspecting and maintaining engine systems must first be broken into their functional parts:

- Screening
- Subsystem inspection
- Component diagnosis
- Maintenance

The screening test in the current environment of voluntary maintenance is performed by the vehicle owner. He decides on the basis of mileage, performance, or operability to have his vehicle maintained. In the latter two cases, the service organization identifies the offending subsystems usually relying heavily on judgmental and qualitative measurements. They may then perform quantitative measurements on components or rely on visually or acoustically sensed qualitative judgments on the state of components and adjustments within the system, often concurrently with the maintenance action. Ideally, one would wish to place these functional elements on a more quantitative basis and, indeed, this is necessary when adapting them to a state inspection. Of specific interest is the determination of the extent to which it is economically feasible to transfer detailed diagnostic activities previously associated with voluntary maintenance to a state inspection process.

In Figure 2-1 generalized procedures are shown in which various levels of diagnosis are transferred from what is routinely the maintenance to the inspection activity.

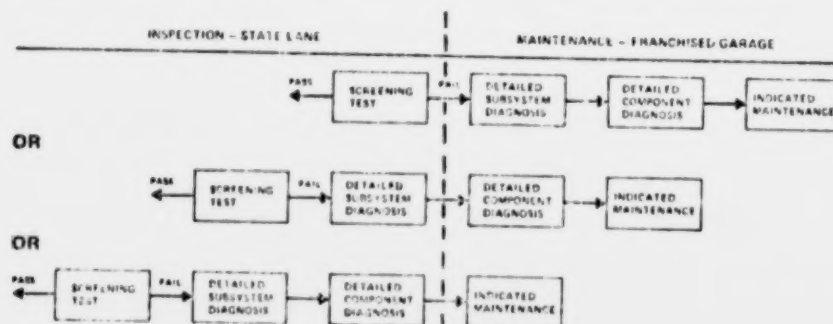


Figure 2-1 Functional Elements of Inspection/Maintenance

An advantage of the above transfer would be that a detailed diagnosis during the inspection process would completely eliminate diagnostic decisions and errors during the maintenance treatment. Because complex and possibly automated instrument systems are required to perform such a diagnosis in a cost effective manner, it may be economical to perform a screening test to limit the number of vehicles subjected to a detailed diagnosis.

As the inspection process progresses from screening to detailed component diagnosis, inspection equipment and labor skill become increasingly important and costly. The probability of correct inspection diagnosis and maintenance repair improves, however, at the expense of higher costs.

As the computer model is currently configured, it may be used to evaluate and optimize procedures based upon the first two approaches to state inspection shown in Figure 2-1.

Quantitative Inspection Criteria

Inspection procedures and criteria for passing or failing vehicles will usually be different depending upon whether the public or private sector performs the inspection because of the factors previously discussed. The model is specifically structured to evaluate procedures based upon:

- Direct measurements of engine parameters (adjustments or malfunctions) using commercially available or more sophisticated garage type equipment.
- Inference of engine parameter maintenance states from indirect measurements such as emission levels under differing engine loads.

Table 2-1 provides a summary of the maintenance options and the emission species affected. The user selects those combinations he wishes to investigate; the computer program may then be instructed to select values of the pass/fail inspection criteria, either placed directly on the engine parameter or on a screening variable, which optimizes the

program figure of merit. Alternatively, if a more restrictive failure criteria is desired to achieve larger emission reductions, the user may directly input his own values of pass/fail criteria.

Maintenance Performed

The model user first specifies those engine parameters he wishes to have maintained in a mandatory program. The choices will depend upon the existing regional air quality and specifically upon those pollutant species which constitute the greatest health and economic hazard (e.g., exceed the Air Quality Act Standards). For example, a region with a chronic photochemical smog problem would preferentially desire reductions in HC and NO_x , possibly constraining the reductions such that a specific HC/ NO_x ratio is obtained. Maintaining parameters related to the induction system in this case may actually be detrimental to the general air quality since CO decreases at the expense of increased NO_x . The model user should select those combinations of engine parameter maintenance options which best satisfy his regional air quality needs. Table 2-1 also provides general information with regard to the relative effectiveness of maintaining specific engine parameters. An estimate of the effectiveness of selective maintenance treatments can be obtained by algebraically summing the appropriate emission index. For example, performing only a complete induction system repair results in factors of +2, +5, and -3 for HC, CO and NO_x , respectively. This particular procedure would not be appropriate in a region concerned with photochemical smog since HC is marginally reduced at the expense of a nearly equal increase in NO_x .

Table 2-1 Maintenance Options Available
within the Economic Effectiveness Model

<u>Engine Parameter/System</u>	<u>Maintenance Treatment</u>	<u>Relative Emission Changes</u>		
		HC	CO	NO
Idle:				
Fuel/air	set rich F/A to spec	+1	+3	0
RPM	set slow RPM to spec	+1	-1	0
Timing	set advance to spec	+1	-1	+1
Ignition:				
Misfire	repair as required	+3	0	0
NO _x Control	repair as required	+1	-1	+1
Induction:				
Air Pump	repair or replace	+1	+1	-1
PCV	clean or replace	+1	+1	-1
Air Cleaner	clean or replace	0	+1	-1
Vacuum Kick	set rich to spec	0	+1	0
Heat Riser	free	0	+1	0
		+2	+5	-3

+ Decrease in emission upon indicated maintenance

- Increase in emission upon indicated maintenance

Numerals indicate relative magnitude of change.

2.1.2 System Constraints

The development and implementation of mandatory program is constrained by a variety of socio-economic and technical factors. These constraints limit the performance and consequently the effectiveness of a given program design. The major constraints presently incorporated in the model are as follows:

- Garage performance effectiveness
- User inconvenience
- Emission inspection reliability
- Basic emission reduction goals

Although general in nature, these constraints affect the various strategies in different ways. For example, the reliability of maintenance for the idle parameters is much greater than for the replacement parameters. Consequently, the overall performance of an idle program will be less effected by this constraint than the more extensive maintenance treatments.

These constraints play a large role in shaping the optimal system design. The constraints built into the present model are static in nature. That is, they remain invariant over time. This assumption results in a conservative estimate of both cost and performance for the developed program. The introduction of technological forecasting into the model would allow for the modification of these constants as new techniques become available.

2.2 SYSTEM DESIGN

The development of an inspection/maintenance system design represents the other major problem in formulating an optimal program specification. The essential design elements are as follows:

- Frequency of Inspection/Maintenance
- Total number of inspection lanes
- Number of inspection stations
- Mobile or fixed sites
- Vehicle throughput rates
- Information processing configuration
- System manpower
- Geographical distribution of stations
- Inspection certification
- Maintenance compliance

Each of these elements contributes in one way or another to the total system design and layout. Under the present study ground rules, a design specification is formulated only for the state lane system. It is assumed that market forces will determine the availability and location of franchised garage service. Determining the optimal inspection period and number of lanes and sites can be accomplished directly with the model.

The key tradeoff in ascertaining the optimal frequency of inspection involves both costs and emission reductions. Short periods of inspection normally yield greater emission reductions at relatively high costs, whereas longer inspection periods produce smaller overall emission reductions at modest costs. Historically, our analysis has shown that a twelve-month period between inspections yielded optimal performance. This result appears consistent with current administrative practices.

The primary tradeoff in determining the number of lanes and sites is basically one of convenience. This decision involves contrasting user inconvenience costs with inspection station capital and labor costs. Labor and capital costs are directly proportional to the number of inspection lanes and sites, while user inconvenience costs vary inversely with the number of sites.

The other variables listed above are best addressed outside the model. The resultant costs from adopting a specific policy, however, can be inputted directly into the model for comparative analysis. The major cost impact from these variables involves the processing of basic inspection/maintenance information. The relatively high costs for this operation can be attributed to the large number of vehicles processed.

3.0 ECONOMIC EFFECTIVENESS MODEL

This section presents a detailed discussion of the basic engineering, economic and system principles used in developing the Economic Effectiveness Model. These principles are embodied in a series of analytical formulations. Each describes one phase of the total inspection/maintenance process. The discussion also focuses on how these modules are integrated together to form the Economic Effectiveness Model. Furthermore, the decision criteria, i.e., figure of merit, used in selecting between various strategies is examined along with other measures of system performance.

3.1 SYSTEM OVERVIEW

A program of vehicle inspection and maintenance involves a complex set of interactions between many components. The several components together with their interactive effects define the inspection/maintenance system. The function of the Economic Effectiveness Model is to provide mathematical descriptions of these components and their interactions and to thus characterize the behavior of the inspection/maintenance process.

Emissions phenomena are crucial components of the system description. The model, therefore, incorporates analytical representations of vehicle emissions. Costs of inspection/maintenance are the other major dimension of the system. The model includes techniques to estimate all costs of an inspection/maintenance program and to link these costs with vehicle emission rates. In addition, the model embodies descriptions of the basic system operations and their interrelationships with system components, and an explicit decision criterion on which to distinguish between program designs. The model performs a statistical analysis on predicted emission reduction and develops a figure of merit based on the statistically significant results. Also incorporated into the model are specialized methods for performing certain data transformations, e.g., integration of emission time histories. Figure 3-1 shows a schematic representation of the basic analytical structure used to describe the process.

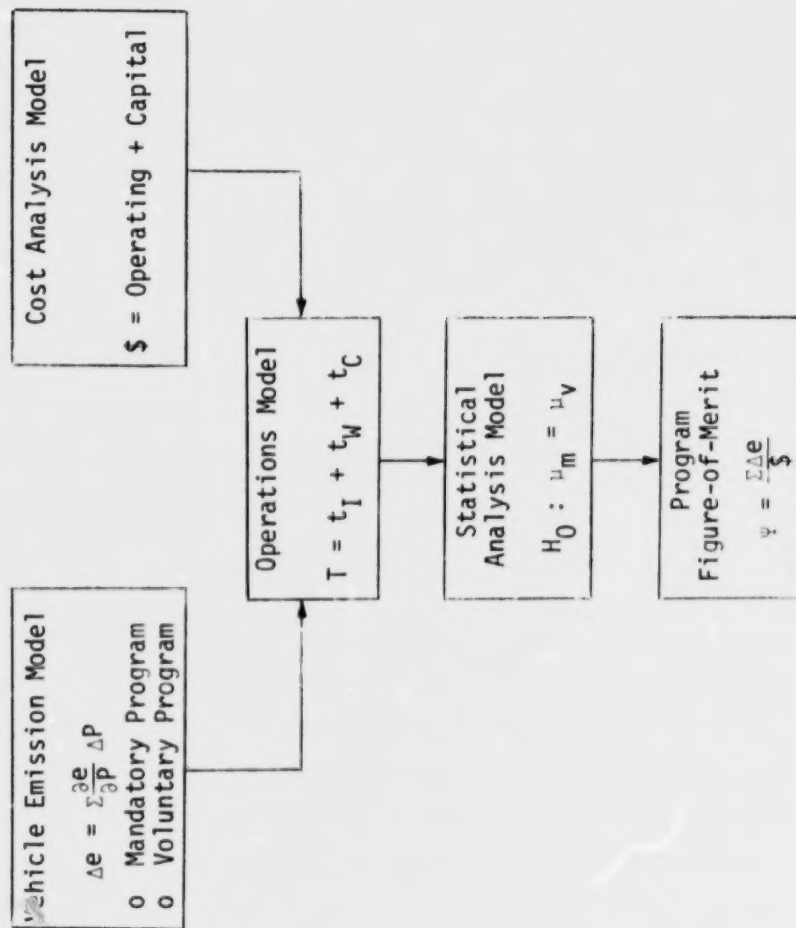


Figure 3-1 Model Schematic

3.2 VEHICLE EMISSION MODELS

The core component of the Economic Effectiveness Model is the vehicle exhaust emissions module. This module describes the process by which vehicles are inspected and maintained, and predicts the resultant emission reductions achieved by the maintenance treatment. This model uses the data developed from the Experimental Emission Test Program (Vol. IV) in characterizing the basic relationships. A list of the major elements comprising the model are given below:

- Inspection
 - Direct engine examination
 - Indirect exhaust emission measurement
- Maintenance
- Deterioration
 - Emission mean values
 - Parameter distributions
 - Mode emission distributions

The following presents a discussion on the structure of each of these submodels and how they are integrated together to yield the required formulation.

The emission related calculation steps for both direct and indirect strategies, are shown in Figure 3-2. Starting at some initial level $\bar{E}$, as determined by the experimental program, the vehicle population emission levels deteriorate over time. At some predetermined interval, the vehicle population undergoes an inspection which will result in a segment of the population requiring maintenance. This in turn will yield an average emission reduction for the total population (as depicted by the Sau-Tootn Curve). The data sets used in characterizing this process is also depicted in Figure 3-2. This process is repeated over the life of the inspection/maintenance program.

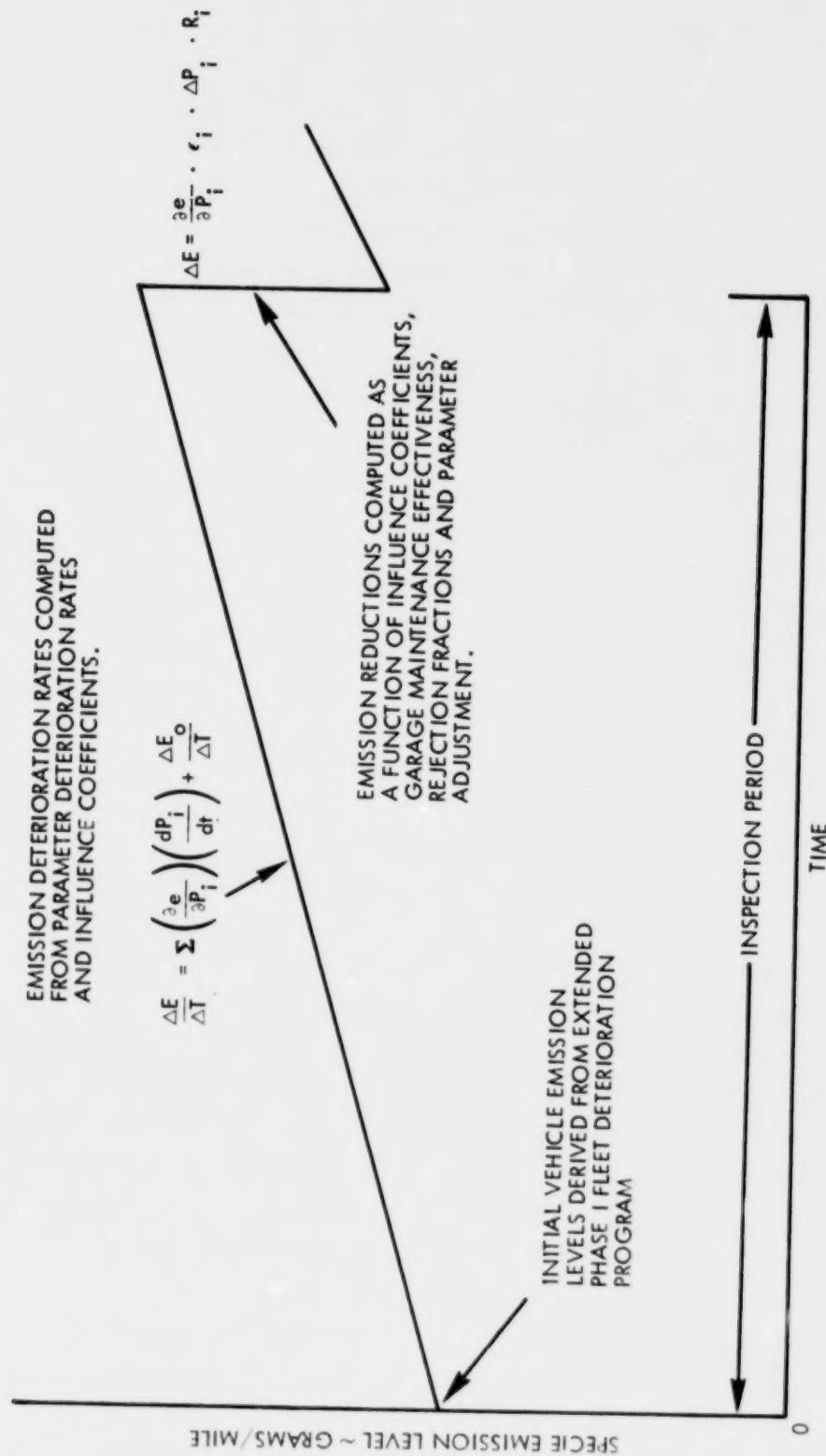


FIGURE 3-2 BASIC COMPONENTS OF PROCESS

The model has been subdivided into three control types and five power trains to reflect the characteristics of specific vehicles. This classification scheme permits the specification of different pass/fail criteria for each control and power train-type. Because of the lack of sufficient experimental data, the model does not presently differentiate between the various classes of power trains.

The model "bookkeeps" the emission levels for each type and combines them to form aggregate levels for the entire population. The composition of the aggregate fleet changes over time as new cars are introduced into the population. Consequently, the importance of the post 1970 fleet grows as time advances. Estimates of the vehicle population mix are made using the Vehicle population Model (see Section 3.6).

3.2.1 Inspection Models

Inspection procedures for testing a vehicle's state involve the quantitative measurement of either engine block components and/or exhaust mode emissions. These parameters and modes are characterized using a set of frequency distributions derived from the experimental test programs. This model can presently accommodate up to ten engine parameters and six mode emissions. A complete list of these elements is shown in Table 3-1. For convenience and effectiveness, these parameter and modes have been grouped into generic engine subsystems. This classification scheme is also shown in Table 3-1.

TABLE 3-1 PARAMETER/MODE CATEGORIES

<u>Subsystem</u>	<u>Parameter</u>	<u>Mode Emission</u>
• Idle	- o Idle A/F - o RPM - o Timing	- o Idle HC - o Idle CO
• Ignition	- o Misfire - o NO_x Control	o Cruise 45 HC
• Induction	- o Air Pump - o PCV - o Air Cleaner - o Vacuum Choke Kick - o Choke Heat Riser	o Cruise 45 CO

An inspection policy statement consequently consists of specifying the subsystem(s) to be tested and the criteria for failure. These two variables, in fact, dictate the level of rejection for a given policy. The percentage of vehicles failing a specific parameter and/or mode emission inspection is determined in terms of a probability distribution and preset pass/fail criteria. Equation 3-1 shows this technique for failing the upper portion of the distribution.

$$R_i = \int_{c.p.}^{3\sigma} P(X_i) dX \quad \dots(3-1)$$

where:

- $P(X_i)$ - Probability distribution for i^{th} parameter
- c.p. - Pass/fail cutpoint
- R_i - Rejected fraction for i^{th} parameter

The same method is used when failing vehicles on the low end, for example, RPM. In those cases the integration occurs between the minus three sigma value and the cutpoint. When the cutpoint equals the lower three sigma limit the probability of failure becomes unity.

The corresponding engine parameter adjustment achieved through maintenance is computed in much the same way. Equation 3-2 shows the basic calculation procedure.

$$\Delta X_i = \frac{\int_{c.p.}^{3\sigma} X P(X_i) dX}{\int_{c.p.}^{3\sigma} P(X_i) dX} \quad (3-2)$$

where:

ΔX_i = average parameter adjustment for maintaining sub-set of population

This gives average adjustment for these vehicles that were maintained. The product of $P(X_i)$ and ΔX_i yields the average adjustment for the total fleet. If the cutpoint equals the lower limit of the distribution, the resultant ΔX_i becomes the mean value. Both of these variables are used in estimating the emission reduction achieved by the maintenance program. Applying the assumption of statistical independence between malfunctions, i.e., $P(X_i \cap X_j) = P(X_i) \cdot P(X_j)$, the most probable total number of vehicles rejected by a given inspection policy is given by:

$$V_R = \left[\bigcup_{i=1}^n P(X_i) \right] \cdot V \quad (3-3)$$

where:

V = total vehicle population

V_R = average vehicle population rejected

$\cup$ = Union of vehicles rejected by inspection

These values are used in computing the cost for a specific program.

Evaluating the effectiveness of inspection based upon measuring exhaust emission involves a further step. The inspection policy statement now evolves around selecting the specific emission signatures for reliably selecting those engine parameter malfunctions to be maintained. The data synthesis leading to the selection of these inspection/maintenance pairs is discussed in Volume IV. The vehicle fraction rejected by the inspection using an emission measurement performed in an operating mode will usually contain multiple parameter malfunctions:

$$P(e_m)_{c.p.} = f \left[P(x_1, x_2 \dots x_n) \right]_{c.p.} \quad (3-4)$$

where:

$P(e_m)_{c.p.}$ = set of vehicles with emissions e_m rejected by cut point, c.p.

$P(x_n)$ = set of engine parameters within $P(e_m)$ to be maintained

The cutpoint on the distribution represents the emission value at which vehicles will be rejected. Some of the vehicles which were rejected by the emission inspection procedure are in the distribution which falls to the left of the optimum parameter cutpoint signifying that repair of these vehicles will not be cost-effective. These errors are termed "commission" errors. The region outside of the parameter distribution $P(x_n)$ but within $P(x_i)$ to the right of the cutpoint represent those vehicles which have been permitted to pass the emission inspection but have excessive parameter deviations from standard manufacture specification. These errors are called "omission" errors. Figure 3-3 shows the relationship between these two types of errors.

The implication here is that an emission inspection does not uniquely identify individual maladjustments but points to failures within subsystems of related engine parameters. These families may usually be classified into a specific subsystem. (e.g., induction or ignition). This is consistent with the fact that the diagnostic modes were shown to point to more than one out-of-specification parameter in the statistically designed experiments (see Volume IV). The development of the relationship between emission inspection signatures and the subsystem maladjustments diagnosed is also presented in that volume and briefly described below.

The errors of commission are expressed explicitly in the model through the use of an inspection efficiency data field. This data has been developed from the engine parameter field survey data by applying the following procedure:

- Inspection cutpoints are systematically placed upon emission mode(s) known to have diagnostic content

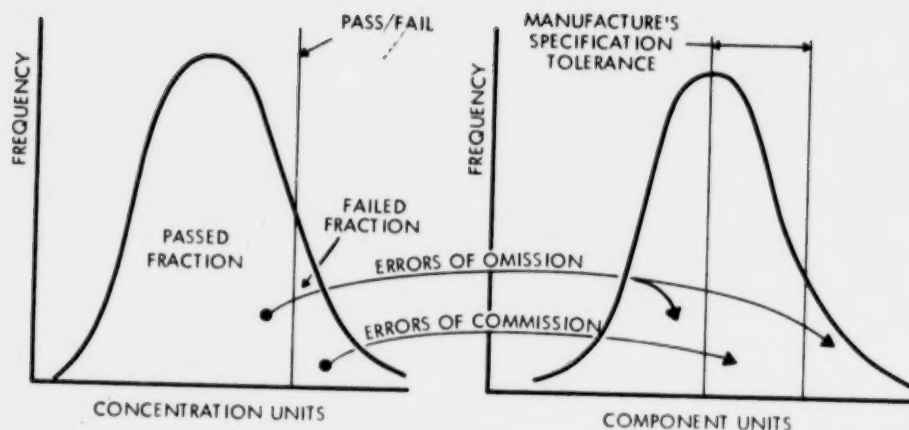


FIGURE 3-3 RELATIONSHIP BETWEEN MODE EMISSION
AND ENGINE COMPONENT DISTRIBUTIONS

- The vehicles so rejected are sorted from the data bank
- Statistical attributes for the appropriate malfunctions found in the data set are developed.

The remaining elements of this process, e.g., maintenance and certification, are identical to the direct inspection approach.

3.2.2 Deterioration of Parameters and Emission Modes

A large, captive fleet of in-use vehicles is being tested to develop the data needed for estimating engine deterioration rates and their effects on emissions. The prime variable is the rate of deterioration of engine parameters from their maintained state. Average emission deterioration rates are developed from two components - those that can be explained by the ten parameters under study and all others (e.g., compression and main carburetor metering). Equation 3-5 presents the relationship used in estimating the emission deterioration rates

$$\frac{\Delta e_j}{\Delta M} = \sum_{i=1}^{10} \frac{\partial e_j}{\partial P_i} \frac{\Delta P_i}{\Delta M} + C_j \quad (3-5)$$

where:

$\frac{\Delta e_j}{\Delta M}$ = 1972 mean emission change with mileage from engine parameter deterioration experiment.

$\frac{\partial e_j}{\partial P_i}$ = influence coefficient for j^{th} emission and i^{th} parameter from orthogonal experiments.

$\frac{\partial P_i}{\Delta M}$ = average engine parameter change with mileage from engine parameter deterioration experiments.

C_j = emission change with mileage because of undefined deterioration factors.

Both $\Delta P_i / \Delta M$ and $\partial e_j / \partial P_i$ as well as C_j are developed from the experimental program. Currently, a linear model is assumed since sufficient data are not yet available for a more sophisticated approach. Rates are assumed independent of inspection interval or degree of enforced maintenance, but are dependent upon the general control system class, uncontrolled, controlled, or NO_x controlled. Generally, the undefined component will become a larger part of the total emission deterioration as the vintage of the vehicle increases. The parameter distributions are inputted into the model and manipulated in tabular histogram form.

The same process is followed in developing the mode emission distributions. The only difference involves substituting the mode emission influence coefficients for the 1972 CVS mass influence coefficients. The model accounts for six emission modes -- IDLE HC, CO, NO_x , loaded HC, CO and NO_x . Currently, neither of the NO_x emission modes are used to diagnose engine malfunctions.

3.2.3 Effectiveness of Maintenance

The effectiveness of maintenance in reducing emissions is estimated from the data acquired in the orthogonal tests and the variables given in Equations 3-1 and 3-2. These tests are statistically designed experiments, wherein engine parameters shown to have a significant impact on emissions were systematically malfunctioned. Response coefficients, changes in emissions per unit change in parameter are derived from these data by applying the condition of orthogonality. The orthogonal experiments resulted in estimates for both the first order and second order influence coefficients,

i.e., $\frac{\partial e_j}{\partial X_i}$ and $\frac{\partial^2 e_j}{\partial X_i \partial X_k}$. The second order, or interactive effects, reflect the experimental fact that emission changes due to simultaneous adjustments of two parameters are not necessarily predicted by the linear sum of the two adjustments taken singularly. One parameter is said to have interacted with the other in this instance.

Equation 3-6 presents the fundamental equation used in predicting the emission reductions achieved from a given maintenance treatment. This is the so-called "Gravitational Law" of vehicle inspection/maintenance.

$$\Delta e_j = \sum_{i=1}^n R_i \cdot \Delta X_i \cdot \frac{\partial e_j}{\partial X_i} \cdot \epsilon_i + \sum_{i=1}^n \sum_{k=1}^n R_i R_k \Delta X_i \Delta X_k \frac{\partial^2 e_j}{\partial X_i \partial X_k} \cdot \epsilon_i \cdot \epsilon_k \quad (3-6)$$

where:

- Δe_j - mean reduction for j^{th} emission
- ϵ_i - maintenance efficiency factor for i^{th} parameter
- $\frac{\partial^2 e_j}{\partial X_i \partial X_k}$ - secondary influence coefficient for j^{th} emission with respect to i^{th} and k^{th} parameters

Equation 3-6 assumes that each parameter distribution is mutually independent of the other. In most cases, the second term, interaction effects, in Equation 3-6 is quite small as compared to the first, approximately five to ten percent effect on the average emission change. These interactions may be extremely important, however, when attempting to explain emission changes due to maintenance for a particular vehicle. The response coefficients provide the key data for transforming engine parameter adjustments to emissions in both the deterioration and maintenance models. The utility of this approach is that it permits the system designer to select only those maintenance procedures which yield the most cost effective results. The maintenance treatment, in all applications,

is accounted for at the end of the deterioration interval. This, in general, leads to a conservative estimate of the total emission reduction achieved by a specific program. This delay in the accounting procedures is consistent with the actual time required to process the total vehicle fleet.

Figure 3-4 summarizes the maintenance and deterioration process for both parameters and emissions. The process shown here starts with a mode emission inspection which in turn identifies a set of parameters to be maintained. These parameter adjustments in turn affect the level and shape of both the model and mass emission distributions. They also affect the level and shape of their own distributions. Following maintenance, each parameter and mode for both the accepted and rejected fleets deteriorate over time to some new state. These states are then pooled to form an aggregate distribution for the various parameters and modes. At that time, these variates are re-inspected and the process is repeated throughout the program time horizon. The technique for the engine parameter strategy is identical except that the mode emission distributions are not analyzed.

3.2.4 Reliability of Maintenance

Controlled experiments have been conducted in which ten vehicles with simulated malfunctions were submitted to approximately 45 service organizations (service stations, independents and new car dealers) for diagnoses and repair. The purpose of these experiments is to determine the reliability and cost of repair for vehicles rejected by the two basic types of inspection, direct engine parameter and emission signature. The post maintenance inspection of vehicle engine parameter states comprise the basic data set describing maintenance effectiveness. Distribution functions developed from these data for those parameters tend toward log normal or bi-modal shapes depending upon whether they are adjustments or component repair, respectively. The bi-modal distribution results because certain malfunctions (e.g., misfire) have not been diagnosed and, therefore, go unrepaired. Both the maintained engine parameter distribution and its geometric mean are used within the computer model to reflect that component of the engine parameter variability resulting from maintenance and the average emission reduction effected, respectively. The influence of over repair is reflected as an actual incremental cost of unnecessary repair.

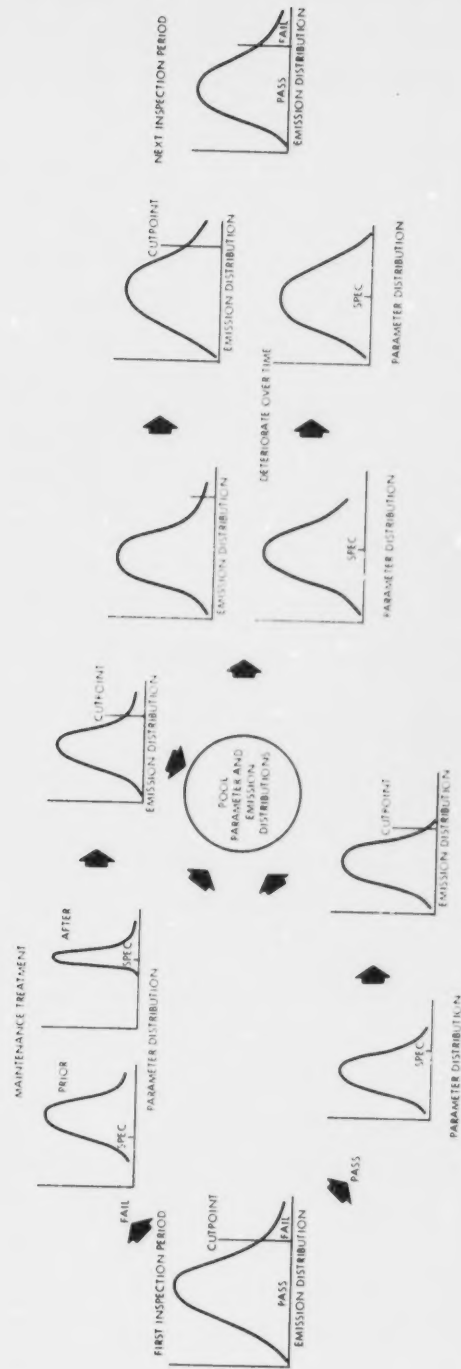


FIGURE 3-4 IMPACT OF MAINTENANCE AND DETERIORATION

It is assumed that this repair, on an average, is ineffective in reducing emissions. This assumption is a reasonable one with regard to the experiment in that a substantial effort was made to assure that all other engine parameters were at manufacturer's specification. In the field some over repair (i.e., exhaust valve repair) may indeed result in emission reduction, albeit at a significantly higher repair cost. This is not expected to influence the estimated program cost-effectiveness figure of merit, cost per weighted emission reductions, although absolute values of cost and emission reductions will be slightly under predicted. The reliability of repair is assumed to be constant over each inspection interval. Presently no quantitative data on how repair reliability might change with inspection interval is available. The reliability of repair is specified in terms of an efficiency factor for each parameter maintained, e.g., the efficiency factor for RPM is 85%. This factor states that on an average, RPM is set .85 of the way to specification or 15% too slow. Equation 3-7 shows the method used for estimating these efficiency factors.

$$\epsilon_i = \frac{\Delta P_i - \Delta P_{i,m}}{\Delta P_i} \quad (3-7)$$

where:

$P_{i,m}$ is the average value of parameter "i" relative to specification achieved by maintenance.

3.2.5 Base Line Emission Prediction

The emission time histories predicted through application of a mandatory maintenance treatment account for only that fraction of the vehicle population which were judged inadequately maintained. The majority of vehicles undergo routine maintenance which also influences the emission and engine parameter time histories. This voluntary maintenance also reflects the present state of vehicle emissions as, for example, measured in the California and EPA vehicle emission surveillance programs. The actual effectiveness of a voluntary program is characterized by several variables, e.g., frequency, extent and reliability. The extent of this maintenance may be deduced through a combination of the influence coefficient and emission and parameter deterioration rates. The technique used in estimating the annual adjustments

achieved by a voluntary program is depicted in equation 3-8.

$$\Delta \bar{x}_B = (\Delta \bar{e} - \bar{c}) \cdot A^{-1} \quad (3-8)$$

where:

- $\Delta \bar{x}_B$ = parameter adjustment for voluntary program (vector)
- $\Delta \bar{e}$ = total emission increase up to deterioration (vector)
- $\bar{c}$ = emission increase due to non-standard parameter (vector)
- A = influence coefficient matrix for all emission species

Both the baseline fleet and those vehicles which passed the inspection undergo the prescribed voluntary program. The actual amount of emission reduction applied to the mandatory fleet is computed by Equation 3-9.

$$\Delta e_j = \sum_{i=1}^n \left(1 - R_i \right) \cdot \frac{\partial e_j}{\partial p_i} \cdot \Delta \bar{x}_{B_i} \cdot \epsilon_i \quad (3-9)$$

where:

- R_i = fraction of vehicles passing the i^{th} parameter inspection

The baseline model also uses the influence coefficient and parameter deterioration rates in predicting vehicle emission levels at various time points. Integration of the difference between the mandatory and voluntary program yields estimates on the reduction of that can be achieved through an inspection/maintenance Program. These estimates are used in formulating the various figures of merit.

The distribution of the inspected variables are also adjusted for voluntary maintenance affects. This adjustment is performed by shifting all of the distribution functions (emission and parameter) by the average values affected by voluntary maintenance, $\Delta \bar{x}_B$. The implied assumption is that voluntary maintenance occurs randomly, all cells in the distribution functions being equally affected by voluntary maintenance.

3.3 ECONOMIC ANALYSIS MODEL

Design of optimal systems of vehicle inspection/maintenance involves the complex interaction of engineering and economic factors. The purpose of the economic analysis model is to translate a set of engineering and operational design characteristics into an equivalent measure of system costs. When combined with the analogous output from the emission models, these cost figures can be employed to arrive at an overall evaluation of the specific system being considered. Figure 3.1 has already shown the basic interrelations between the economic and other factors characterizing the inspection/maintenance process.

This characterization focuses directly on the cost effectiveness of the inspection/maintenance program. It attempts to compare the achievement per unit cost for a specific program design with similar figures from alternate programs. In this comparison, achievements and costs are both narrowly defined to be consistent with both program perspective and the realities of quantifiability. Specifically, achievements are measured in equivalent tons of reduced emissions and costs are based upon tangible use of resources. This approach is to be distinguished from a cost/benefit analysis of the same problem. The latter is based upon a much broader definition of both system costs (tangible and intangible) and achievements (tangible and intangible). Due to limits on our ability to quantify accurately elements of these broader definitions, a cost/benefit analysis of inspection/maintenance programs would be much more qualitative in nature. The narrower focus of cost effectiveness is more consistent with both the goals and scope of the current study and is therefore reflected in the economic model described below. It attempts to address cost and achievement elements, which are realistically quantifiable without implying that all such system elements are accounted for. The latter would require subjective estimates and interpretation beyond the scope of this effort and, indeed, beyond the current state-of-the-art.

3.3.1 Outline of Economic Model

The economic analysis model is shown schematically in Figure 3-5. It operates on basic system design data to generate, ultimately, estimates of total annual system costs. The relevant costs here are the explicit and implicit costs to implement the program. Explicit costs include expenditures to construct facilities and to perform inspection/maintenance operations. Implicit costs are less tangible and generally are not expressed in monetary units. They include, for example, the time the vehicle owner spends in inspection and maintenance related activities. Station location and configuration design are determined by considering both types of costs.

Inspection, maintenance and user-time costs comprise the main elements of the economic analysis model. The model estimates capital and direct operating costs for both the inspection and maintenance processes. Capital costs considered are those for equipment, land and facilities. Operating costs include utilities, labor, materials, spares, fringe benefits and general administration. All capital costs are discounted over a specified period and are added to the projected direct operating costs to obtain total annual operating costs. Total program costs over the time period considered are computed as the sum of these annual operating costs, discounted to present value. These costs are quoted exclusive of the user inconvenience costs which are included in the evaluation of alternative inspection/maintenance processes.

3.3.2 Major Elements of the Model

It is useful to divide the basic components of the economic analysis model for the test population into two groups: those that estimate direct or explicit resource costs of the program and those that estimate indirect or implicit resource costs.

Explicit Cost Components

Explicit costs are the common costs related to the real exchanges of funds for materials, goods and services.

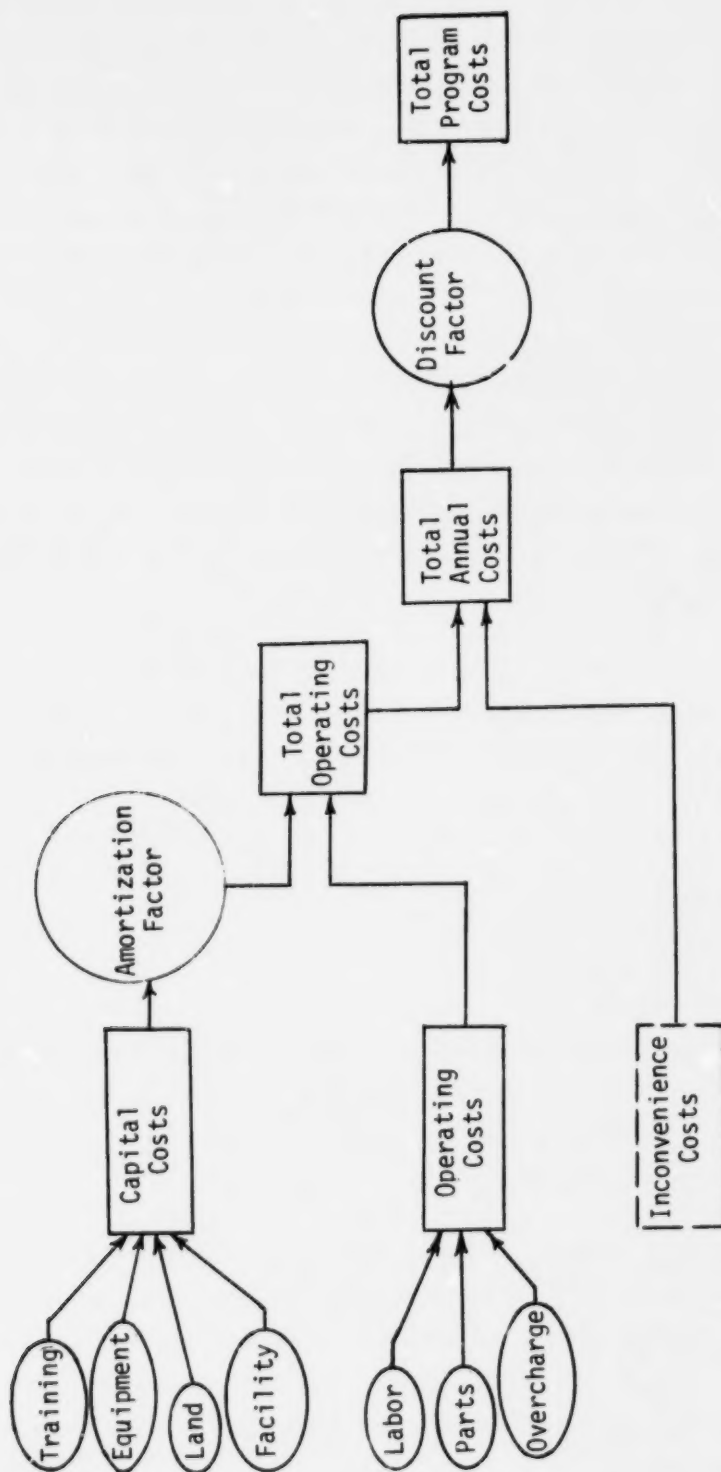


FIGURE 3-5 COST ESTIMATOR MODULE

Capital costs are a major form of explicit system costs. The costs associated with capital investment requirements are a function of the basic inspection/maintenance strategies. For the case of a franchised-garage system, no direct capital investment will be accounted for in the program. This assumption presupposes that franchised licenses will be awarded only on condition of a satisfactorily equipped garage. The state inspection/franchised-garage maintenance strategy does require a capital investment for the inspection facilities. These costs will depend on the size of the car population, the length of the inspection interval, and specific instrumentation and equipment requirements. In the model, it is assumed that all investments come onstream at time zero and that no existing state facilities are employed. Separate investment calculations are performed for the building, land and equipment requirements for each state-lane station. These calculations involve a scaling operation based upon unit inspection and unit maintenance facilities defined in the system design.

The contributions of these capital investment costs to annual costs as indirect operating costs are computed using the concept of a sinking fund. For the case of the facility for a single inspection station, this relation is:

$$SF = \frac{(1 - \lambda) \cdot i \cdot (1 + i)^n}{(1 + i)^n} + i \cdot \lambda \quad (3-10)$$

where: SF = Sinking fund factor
 i = Rate of interest
 n = Amortization period
 λ = Salvage fraction

This can be interpreted either as financing through bonds which are payable in full upon maturity or through internal funds which must be replaced in full at the end of a fixed period. Analogous calculations occur for all other investment categories.

For each inspection interval, direct operating costs must be added to the above indirect operating costs to obtain the total system operating costs. Under the direct category are separate calculations for wage costs, administrative costs and miscellaneous operating costs for both inspection and maintenance. In addition, a charge for labor and parts is

incurred under the maintenance activity. Wage costs for a single station are broken down into two portions: costs incurred at straight-time over the normal working day and costs incurred at a specified overtime rate to service the queue remaining at the end of the normal working day. Miscellaneous operating costs reflect such items as electricity and certain basic supplies.

Implicit Cost Components

The system costs discussed so far are only part of the total program costs. We must add to these explicit costs an estimate of the implicit cost represented by driver inconvenience. These implicit costs reflect resource expenditures on the program that are not accompanied by a real flow of funds.

The total time spent by users whose vehicle passed the inspection is considerable, and it is reasonable to expect that, without an imposed program, this resource would be employed in other pursuits from which the individual would derive a benefit. The model, therefore, computes a monetary estimate of these lost benefits which compose the value of private time expended on the program. It does this by computing the driving time to and from the station and waiting time at the station. Waiting times at inspection station locations are defined from a queueing model. This model assumes a Poisson distribution of vehicle arrival times at the inspection station. Adding the traveling time and waiting time to the actual vehicle inspection time yields the total inconvenience time. For the case of the emission signature inspection, an added processing time for some vehicles is incurred for reinspection. This additional time is charged against the program if the failed vehicle passes its second inspection. No user time charges are allocated for the corresponding maintenance activities since they constitute the compliance element of the program.

The conversion of these times to a direct dollar amount is done using a social cost of \$2.00/hour. Thus, a direct comparison can be made between these costs and the designed facilities costs. The more stations deployed in the system, the lower the social cost to the public and

vice versa. One of the more essential dimensions of the system design is the tradeoff to be made between explicit and implicit costs to obtain the most cost-effective inspection/maintenance program.

Costs of the Base Population

All of the above costs refer to the resources necessary to implement a given inspection/maintenance program. Under certain situations, the relevant cost figure for evaluative purposes is the difference between this system cost and that incurred under normal vehicle maintenance. As shown in Figure 3-1, cost data for the base case can also be generated by the economic analysis model. It is assumed that normal maintenance occurs over periods identical to those imposed in the inspection/maintenance program. Unit cost figures describing average maintenance costs for the age and distribution of the base population are employed together with average maintenance intervals to obtain an estimate against which the inspection/maintenance program costs can be compared.

3.3.3 The Effect of Time on Costs

The phenomena - economic and emissions - that relate to an inspection/maintenance program are basically dynamic in nature. Time enters as a variable and all events take place over a specified time span. To neglect the effect of time is to neglect a crucial dimension of the problem.

The economic analysis model includes explicit procedures to account for time effects on system costs. These procedures can be broken down into two categories - inflating and discounting costs.

Inflating Costs

A fundamental problem in measuring costs relates to the nature of the monetary unit. While it is essential to have a constant monetary unit upon which to base cost calculations, in reality, this unit varies over time. If we desire to compare costs with reference to the initial year as a datum level, the program will compute all costs in constant dollar figures (constant here implies the use of a monetary unit whose value in each year is equal to that of the initial year). On the other hand, we

may recognize the variation of prices over time and choose to base cost calculations on current rather than constant cost concepts. While the first approach is valid for comparing relative resource usage in various years, the latter is valid for comparing out-of-pocket costs. For comparison of current dollar costs, the program includes provisions for inflating all costs at a constant annual rate. The results presented to date, however, do not include the effects of inflation.

Discounting Costs

Examination of the impact of time on systems costs leads to a further observation. Not only may prices rise in time but a dollar spent in the future is not equivalent in value to a dollar spent today. Time itself has value and this is a reflection of the availability of alternative productive uses of funds. Because of available mechanisms for employing funds productively and, thus, earning an interest or profit, it is not realistic to weigh a dollar cost incurred today on an equal basis with a similar cost incurred at some future date. To compare future costs with present costs, the former must be discounted to present value by a discount rate related to the productivity of capital or the going market rate of interest. Equation 3-11 gives the discount rate expression used in the model.

$$DR_n = \frac{1}{(1 + i)^n} \quad (3-11)$$

where:

DR_n = Discount factor for n^{th} period
 i = Interest rate
 n = Program period

All costs are therefore discounted at an assumed constant annual rate to permit comparisons of system costs on the basis of present worth.

3.3.4 Other Economic Factors

Two additional economic factors have been incorporated into the model in an attempt to account for costs associated with operationalizing the system. The first one involves the so called "overcharge" phenomenon

observed in the franchised garage experiment. The actual price charged for both inspection and maintenance was, in a number of cases, several times greater than the predicted cost[2]. An estimate was made on the average amount of overcharge for the three inspection/maintenance strategies. These costs are now included as part of the program's operating expense.

The cost associated with the training of inspection personnel represents the second economic factor added to the model. These costs account for the time required to train personnel to operate a statelane inspection station. The planned training program consists of three distinct phases:

- Classroom lecture
- Laboratory demonstrations and equipment maintenance
- On-the-job training

The cost per employee for the training program has been estimated at \$500.00. The model treats the total cost of training, i.e., cost per employee times number of employees, as an initial investment. This investment is amortized over the time horizon of the inspection/maintenance process, e.g., 5 years, and then included as part of the annual program operating cost.

Another economic factor pertaining to the implications of vehicle maintenance on fuel consumption has also been examined. The repair or adjustment of ignition system components, specifically misfire, will result in a favorable improvement in fuel economy. This situation can be attributed to the decrease in unburned hydrocarbons achieved in the combustion process. A preliminary analysis of potential fuel savings yielded a rough estimate of approximately \$1.00 per car per year for the total population. This analysis was based on an average fuel cost

of \$300.00 per year and an average misfire rate of 0.0035 percent. While the cost reduction appears significant vis-a-vis training cost and user time cost, it has not been incorporated into the model. This is because of the uncertainty in the basic estimate and the fact that such savings would be applicable to only one of the candidate strategies, i.e., ignition tune-up.

3.3.5 Total System Cost

In summary, once system investment costs have been computed, the model evaluates the indirect and direct operating costs and the private user costs for the inspection/maintenance process at each inspection period. These costs are summed for a single interval, discounted by factors appropriate to the end of that interval, and the summed overall intervals to provide a measure of total program costs. This total cost figure enters directly into the figure of merit calculation as depicted in Figure 3-1. It is given by:

$$TAC = \sum_{i=1}^n DF_i \cdot AOC_i \quad (3-12)$$

where:

- TAC - Total annularized cost
- AOC_i - Annual operating costs for i^{th} year
- n - Number of years in program
- DF_i - Discount Factor

3.4 OPERATIONS RESEARCH MODEL

That portion of the Economic Effectiveness Model concerned specifically with facility sizing and configuration is termed the operations research model. It describes the interrelationships between the number of stations, number of lanes per station, length of servicing queues, and amount of user inconvenience time involved in the actual operation of the inspection/maintenance program. Separate models of each related activity and their interactions are specified analytically.

For a given number of servicing lanes in the total system and a particular size of facility in terms of lanes per station, the model determines the required number of sites. The number of sites combined with the car population and inspection interval set the mean arrival rate and this figure, together with the inspection time and the station size, yields the facility utilization factor.

The mean length of the service queue, L , can be established by assuming a Poisson arrival distribution:

$$L = \frac{P_0 \left(\frac{\lambda}{\mu} \right)^S}{S! (1-\rho)^2} \quad (3-13)$$

where:

P_0 = the probability of the service queue being of zero length

λ = mean arrival rate

μ = service rate = inverse of inspection time, t_j

S = number of lanes per station

ρ = utilization factor

The waiting time in the queue follows directly as:

$$t_w = \frac{L}{\lambda} \quad (3-14)$$

Given a region of total area A, N sites and an average vehicle speed of θ , the commuting time for the individual is estimated as:

$$t_c = \frac{2 \cdot \left[\frac{A}{N} \right]^{1/2}}{\theta} \quad (3-15)$$

The total impact of system operations on user time is then simply:

$$\text{Total inconvenience time} = t_i + t_w + t_c \quad (3-16)$$

3.5 STATISTICAL MODEL

The results derived from the Economic Effectiveness Model are basically deterministic. That is, the predicted emission reductions are computed utilizing fixed relationships for each operational step. Obviously, a real program of vehicle inspection/maintenance involves activities which cannot be characterized deterministically. For example, consider the impact of maintenance effectiveness on overall program performance. This uncertainty in inspection effectiveness is directly translated into uncertainties in predicted emission reductions. It becomes important, therefore, to ascertain the statistical significance of predicted emissions reductions. The selection of an inspection procedure based on the computed figure of merit may be inappropriate since the estimated emission reductions may not be statistically significant.

To evaluate the implications of the program uncertainties, a statistical inference model is incorporated within the Economic Effectiveness Model. The function of this model is to:

- Test whether model predicted emission reductions are statistically significant (i.e., greater than zero)
- Estimate confidence limits on statistically significant emission reductions
- Estimate confidence limits on the emission time history profiles.

The model utilizes the emission predictions for both the baseline and test fleets to perform these various statistical tests.

Fundamentally, the statistical model is designed to generate the variance for the distribution of emission reductions achieved by the inspection/maintenance program. When combined with the mean values generated by the emissions model, one can perform a formal statistical test on the significance of reductions achieved under required inspection/maintenance. This general process is shown schematically in Figure 3-6.

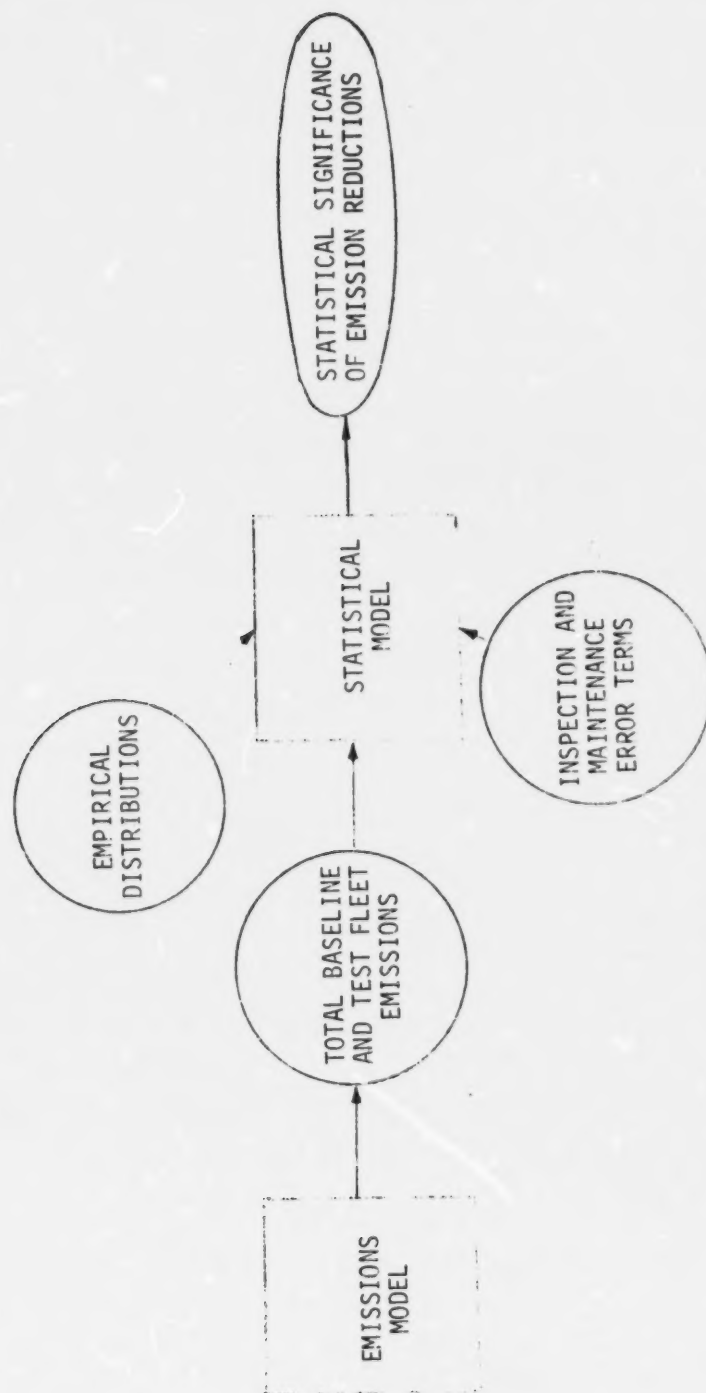


FIGURE 3-6 ECONOMIC EFFECTIVENESS STATISTICAL MODEL

There are four principal objectives associated with the construction of the statistical model. The first is to determine the uncertainty distribution of mass emissions for the test population and the base population at several times during the process. The second objective is to determine the uncertainty of the integral of the emission reduction, i.e., total integrated tons, periodically and at the end of the process. The third one is to determine the probability at each of these time points that the mean emission difference is greater than or equal to some specified constant. The final objective is to determine the difference in the integral emission reductions which is significant to the same confidence level at the end of the process.

There are two distinctly different approaches that can be taken to test the significance of analytically estimated emission reductions. Both are incorporated within the statistical model and can be employed on an optional basis. The first utilizes empirically derived aggregate distributions on HC, NO and CO obtained from the fleet experimental program (Vol. IV). Variances obtained from these distributions are then used to test the significance of model results. This method was the first to be employed by virtue of data availability as established by the emission test program. It is feasible, however, only for the extensive B or major tune-up strategy.

The second approach utilizes an analytical procedure for estimating variances on emission reductions. In this case, these variances are built up from basic error information.

The main sources of uncertainty in predicting the performance of candidate inspection/maintenance programs can be divided into two sets. The first set consists of those uncertainties associated with the inspection/maintenance process, namely:

- Inspection measurement variance (i.e., instrumentation)
- Maintenance reliability

The other set entails those uncertainties in the actual emissions data base. These uncertainties are due to the fact that attributes of

the total population have been estimated from relatively small samples. In the case of influence coefficients derived from the orthogonal experiments, the selected 11 cars were assumed to be characteristic of the total population. The chief sources of uncertainty in the emissions data base are:

- Correlation of emissions-to-engine parameter variation (i.e., residual error from orthogonal experiments)
- Vehicle manufacturer-to-manufacturer emissions variability
- Emissions variability caused by out-of-specification engine parameters (a function of maintenance state).

The emission distributions for each specie are estimated during each inspection/maintenance period using the distributions for the previous period convoluted with the maintenance effects and associated error terms. These distributions are then statistically compared with those for the baseline fleet as in the alternate procedure.

The analytical procedure is obviously much more flexible. Unlike the empirical approaches, it relies on fundamental error data which is independent of inspection/maintenance strategy. It can, in principle, be employed to assess the uncertainties associated with any inspection/maintenance strategy.

The variances obtained by one of the above alternatives are then combined with mean emission values estimated by the emissions model for both baseline and test fleets to determine the statistical significance of the estimated reductions (see Figure 3-1). The standard "t" score statistical test is used in comparing these resultant test and base distributions. The null hypothesis used to test whether the two samples came from different populations, i.e., that the means are significantly different, is:

$$H_0: u_T = u_B \quad (3-17)$$

where: u_T = test mean
 u_B = base mean

The alternative hypothesis is:

$$H_1: u_T < u_B \quad (3-18)$$

If the analysis produces a positive test, the null hypothesis can be rejected and that a difference in means does exist (accept H_1). Utilizing the computed statistic, we can also establish confidence limits around the predicted emission reduction at each time point:

$$a \leq \bar{x} \leq b \quad (3-19)$$

where:

a = lower confidence limit

b = upper confidence limit

$$\bar{x} = x_B - x_T$$

If two-sided 90% confidence limits are placed on the distribution, then it can be stated that there is a 90% chance that the predicted emission reductions will fall within these limits. If a one sided test becomes desirable, it can be stated that there is a 90% chance that the emission reductions will exceed the value a.

The figure of merit can now be recomputed using the statistically significant emission reductions. Once this has been accomplished, the various inspection/maintenance procedures can be reordered based on the revised figure of merit. The reordered set can then be compared to the initial set to determine whether the relative attractiveness of the candidate procedures has been altered.

3.6 UTILITY MODELS

The present Economic Effectiveness Model employs a wide variety of utility routines and algorithms. These are used for performing the quantitative calculations required to complete the analysis of a specific inspection maintenance strategy. The two most salient routines consist of an integration package and a probability function algorithm. The integration routine (which employs an Euler method) computes the total exhaust emissions by weight over the program's time horizon. These results are utilized directly for developing the program's figure of merit. The probability function algorithm provides estimates on vehicle subsystem and population rejection fractions using the basic parameter and/or mode emission distributions. This function is composed of Boolean expressions for estimating both the union and intersection of selected parameter and/or mode emission sets. These calculations are performed based on the fundamental assumption that all parameters and all mode emissions are independent. Empirical estimates have indicated that while this is true for parameter distributions, such is not the case for the mode emissions, especially the idle measurements. A control probability component has been incorporated into the probability function to account for the observed interdependence.

Another important routine in this group is the vehicle population model. This model provides estimates on the attrition rates and new car compositions for each year of the inspection/maintenance process. This model, in effect, removes most of the restrictive assumptions regarding the size and characteristic of the vehicle population to be studied. The model will simulate the quantitative change in population as more new cars (post 1970) are introduced while pre-control (pre 1966) and control (1966-1970) leave through natural attrition. The net result will be a considerable improvement in aggregate emission levels and therefore the validity of inference drawn from estimated emission reductions. The demographic data can be incorporated into the model for conducting comparative analysis.

In addition to the aforementioned models, a number of smaller routines are utilized in the calculational process. They include:

- Linear interpolation algorithm
- Two-dimensional emission time history plotter
- Legendre polynomials curve fit
- Statistical routine for computing mean and standard deviation of functional distributions.

The interpolation algorithm is used in developing the parameter and/or mode emission frequency distributions for the next time point. The analytically derived emission time histories are based on a Legendre polynomial curve fit of the numerical data.

3.7 DECISION CRITERION

Up to this point, we have described the manner in which the simulation model computes measures of emission levels and relevant costs for a given policy statement regarding vehicle inspection and maintenance. We need now to identify an acceptable selection criterion which embraces with a single value a measure of the goals of the program. Comparison of different values of the figure of merit permits rapid assessment of relative economic effectiveness of various policies. Ideally, then, we would select that policy set (i.e., inspection interval, emission level, pass/fail criteria, etc.) with the "best" figure of merit. Here, the term "best" refers to the lowest value of the figure of merit.

Unfortunately, no one figure of merit appears to include all of the desired characteristics. The simulation model instead has the capability of examining several different figures of merit, thus permitting a determination of the sensitivity of the optimal decision to the chosen objective function. The most relevant figure of merit can be expressed by:

$$\text{Figure of Merit} = \frac{\text{Program Cost}}{\sum W_j \cdot \Delta E_j} \quad (3-20)$$

where:

- W_j = weighting function for each emission specie
- ΔE_j = emission difference between baseline and test program

This relationship provides a basis for comparing the voluntary and mandatory programs with the cost of the mandatory program. The figure of merit units are in discounted dollars per weighted tons of emission reductions. Thus, program effectiveness can be read in terms of so many dollars to achieve a reduction of one composite ton.

As can be seen, the weighting function establishes the degree to which emission specie reductions impacts the program design. Having fixed the weighting of emission reductions the model can determine the optimal pass/fail criteria and system design for the several proposed inspection/maintenance strategies. In actuality, the weighting of emission reductions must reflect the air pollution problem of the various

urban centers. Since some regions are more concerned with high ambient CO levels than with HC levels, they would weigh CO reductions higher than those of HC or NO.

The mechanism for actually determining the most attractive policy set from among the several proposed inspection/maintenance approaches should include not only the figure of merit, but also the inspection costs per car and attendant emission reductions. These latter two parameters are important in that they relate to the practical aspects of emission control. For example, it could be assumed that a program producing emission reductions less than 5%, no matter how economically attractive, would not be very effective as a control scheme. The guidelines selected for this study are in the form of the following cost constraints and emission reductions goals:

- Average cost of six dollars per car for an idle program was the maximum allowable
- A program which provides emission reductions (HC and/or CO) of less than 5% was unacceptable.

These guidelines, when used in conjunction with the figure of merit, provide the criteria for analytically identifying the "best" inspection procedure and system design.

Each combination of inspection procedure and system design can be looked upon as a strategy. By examining the various strategies with the economic effectiveness model, an ordinal ranking of these strategies based on their figures of merit can be developed. It becomes fairly straightforward to then identify the optimal strategy by merely selecting the one which ranks first and conforms to the cost and actual emission reductions guidelines described above.

4.0 ANALYTIC METHODS OF SOLUTION

The above sections of this report have described the elements of the mathematical model of an inspection and maintenance system. These elements include both a data base which describes empirically the magnitudes of system components and a methodology which integrates and synthesizes the data into a coherent description of the system performance. In this section, several uses of the model will be described. Each of these uses or modes of operation provides a distinctly different method for investigating the properties of a particular inspection/maintenance design and for drawing inferences regarding its attractiveness.

There are essentially three operational modes in which the model can be employed:

1. Simulation
2. Optimization
3. Sensitivity Analysis

Each of these modes will be discussed in detail below.

4.1 SIMULATION

Simulation is conceptually the simplest mode in which the Economic Effectiveness Model can be operated. It represents a first order attempt to investigate the nature and interactions of a specific inspection/maintenance program design.

To perform a simulation, one must assign explicit values to all system independent variables. These are the strategic and tactical variables available to the policy maker in designing an inspection/maintenance program (e.g., inspection interval and number of lanes per station). Given a complete definition of the policy to be examined, the Economic Effectiveness Model will simulate the behavior of the system in response to that policy. This simulation involves estimating the dynamic character of the various phenomena of concern - costs and emissions - and summarizing the overall results of the policy in a figure of merit. Simulation is then a procedure for predicting the impact of a given inspection/maintenance policy on the economics and emissions behavior of the system.

4.2 OPTIMIZATION

Optimization implies a step beyond pure simulation. It attempts to employ a series of simulations to identify the set of values of system design variables that lead to the best system given a specific decision criterion. The discussion of optimization which follows is divided into two parts. First, the general methodology of optimization is explained. Second, linear programming, a particular optimization technique which is used to perform certain optimizations of subsystem variables, is described as it relates to the system model.

4.2.1 General Optimization Methodology

Values of system variables which optimize simple nonlinear or complex linear mathematical models can often be found by means of rigorous analytical techniques. Given, however, a complex nonlinear system such as the inspection/maintenance model, rigorous procedures are of little value. Resort must then be made to numerical heuristic methods to obtain an approximate set of optimal system design variables. This involves the use of a series of system simulations in sequence to parametrically step towards the optimal system design. One of the decision criteria described above is used to determine the optimal value of a particular system design variable. In principle, the procedure would proceed along these lines:

- A. If there are n system design variables X_i ($i = 1, \dots, n$), conduct a series of simulations in which values of X_j vary discretely over a relevant range while values of X_i ($i = 1, \dots, j-1, j+1, \dots, n$) are held constant at predetermined levels.
- B. Given a decision criterion $C = f(X_1 \dots X_n)$, identify the value X_j^* which maximizes (or minimizes depending on the nature of C) the value of C .
- C. Focusing now on X_k ($k \neq j$), conduct a series of simulations in which values of X_k are varied discretely over a relevant range while values of X_i ($i = 1, \dots, j-1, j+1, \dots, k-1, k+1, \dots, n$) are held constant at predetermined levels and $X_j = X_j^*$.
- D. Given a decision criterion C , identify the value X_k , which optimizes C .
- E. Continue in this manner until optimal values of all system design variables have been identified.

While the above parametric optimization procedure, in the limit, requires considerable iteration to converge on an exact set of design values, it leads quite rapidly to an approximate optimal set which is sufficiently accurate for most purposes. This set, then represents the design of an optimal inspection/maintenance system based on the selected figure of merit and the particular system class being examined.

4.2.2 Linear Programming Algorithm

For large sets of independent variables, the above procedure would be prohibitively expensive. To reduce analysis costs, and in recognition of their varying impact on system design, an optimum set of engine parameter or mode emissions pass/fail criteria is estimated via a linear programming algorithm imbedded within the larger system model.

Linear programming offers a useful, approximate solution to the problem of identifying optimal values for the above variables. A computational sub-loop estimates locally optimal cut points by means of the linear programming algorithm. The relationship between the objective function of the linear program and its independent variables X_i used in this application, i.e., engine parameter rejection rates is given below.

$$Z = \sum_i \sum_j \frac{\partial e_j}{\partial p_i} W_j \Delta X_i \cdot R_i$$

where:

$\frac{\partial e_j}{\partial p_i}$ = change in emission of j^{th} specie per unit change in i^{th} parameter setting

W_j = relative weight assigned to j^{th} specie.

ΔX_i = average parameter adjustment for failed vehicle

R_i = failure probability for i^{th} parameter

The objective function, Z , is the weighted reduction in emissions achieved by maintenance and the problem is to identify specific values of R_i which maximize Z .

This maximization may be subject, however, to two basic classes of inequality constraints:

1. That the emission reduction for each specie exceeds a threshold level

$$\sum_i \frac{\partial e_j}{\partial p_i} \Delta x_i R_i \leq b_j$$

where: b_j = threshold reduction for j^{th} specie

2. That the average cost per vehicle per inspection not exceed a given value

$$\sum_i d_i R_i \leq g$$

where: g = maximum allowable cost per car

d_i = prorated cost per unit adjustment of the i^{th} parameter

The b_j 's are normally expressed in terms of some minimum percentage emission reduction desired for each exhaust pollutant, e.g., 10% HC and 10% CO reduction. These values are exactly analogous to the emission reduction program goals employed in earlier studies. The cost constraint equation is used to relate the cost of adjusting or replacing engine parameters with total system costs. The g coefficient represents an assigned program cost for a given inspection/maintenance procedure that cannot be exceeded.

The above linearized version of the pass/fail determination procedure will yield estimates of the optimal rejection factors for each parameter. These estimates can then be employed to develop values of the optimal cut points of each parameter in the inspection process through an iterative scheme.

This iterative scheme first computes for the rejected vehicle population a set of mean value engine parameter settings. Using the basic engine parameter distributions, a systematic search is made to find the pass/fail criteria which will yield the optimal rejection fraction. In this manner, then, a linear programming algorithm can provide an approximate mechanism for determining pass/fail criteria for multi-parameter inspections. The

same basic technique can also be used in deriving mode emission cut points for the emission signature strategy.

This method of estimating optimal values of these design variables is used only at the initiation of any particular simulation, although it could be extended to each time point if system sensitivity warranted. In effect, then, within each simulation is a sub-optimization of inspection pass/fail criteria. Parametric optimization described above is necessary only to determine optimal values of the remaining system design variables.

4.3 SENSITIVITY ANALYSIS

Sensitivity analysis is in a sense a halfway house between simulation and optimization. It involves more than merely estimating the impact of a specific policy on a specific system, yet stops short of identifying optimal values of system variables. Specifically, sensitivity analysis utilizes a sequence of simulations to determine the sensitivity of key analytical results to changes in a particular element of the system model. These simulations involve analysis of policy designs and system definitions that vary only in the value assigned to the particular element being examined. In this manner, the impact of that element on system behavior can be isolated through parameterization of the value of that element, all other design and system values being held constant.

Sensitivity analysis can be performed to establish the effects on procedure effectiveness and selection of:

1. Changes in assumptions or ground rules of the model
2. Changes in policy variables
3. Changes in empirical data employed in the model.

An important aspect of a sensitivity analysis involves defining a so-called nominal or standard case. The impact of various changes in system input on program performance is then measured relative to this reference. The nominal case selected as a reference is typically an idle parameter inspection/maintenance program for the Los Angeles basin. If desired, assessment can also be made of the influence of system variables on the performance of a program which involves more extensive inspection and maintenance. Presented in Appendix A are several examples of program assumptions which can be investigated using sensitivity analysis.

4.3.1 Model Structure

The model incorporates specific assumptions regarding the extent and frequency of voluntary maintenance. These characteristics have direct bearing on the predicted baseline emissions levels and therefore on emission reductions predicted by the model. More frequent and/or more extensive voluntary maintenance implies lower baseline emissions and potentially lower reductions for a mandatory program. The reverse is also true. By varying voluntary maintenance behavior, one can determine the sensitivity of policy selection to assumptions made in this area.

Maintenance effectiveness assumptions are also built into the model. Obviously, the degree of effectiveness of maintenance performed under the inspection/maintenance program determines, to a major degree, the reductions achieved under the program. Various assumptions can be made regarding maintenance effectiveness and simulations can be performed to establish the impact of maintenance variations on program success.

An important ground rule of the model involves the decision criterion. Yet, it was stated earlier that no single criterion is perfectly acceptable. It is crucial, then, to determine the sensitivity of program selection to the particular criterion employed. This, too, can be established via a series of simulations of the same group of policies but using different decision criteria.

4.3.2 Program Variables

The length of the inspection interval is closely connected to both system costs and emission reductions. The shorter the interval, the greater the costs but also the higher the reduction in emissions. On the other hand, the longer the interval, the lower the costs and reductions. The establishment of the exact sensitivity of the figure of merit to variation in inspection interval is crucial to understanding the nature of the inspection/maintenance system and ultimately to identifying an optimal design.

This is also true for the number of lanes per station. More lanes mean more capital investment but lower user inconvenience with the reverse also true. Design of the most economically (i.e., socially acceptable) effective inspection/maintenance program requires the estimation, therefore, of the sensitivity of the figure of merit to variations in the number of lanes per station.

4.3.3 Empirical Data

Parameter deterioration rates represent a key dimension of the empirical description of the emissions phenomena in the model. They determine the degree to which maintenance is required as well as the success of any maintenance activity. Higher rates mean more frequent maintenance and higher reductions. Analytical results must be examined over a realistic range of deterioration rates to establish the related range of economic effectiveness of an inspection maintenance policy.

The actual effective reduction of any program is computed as a weighted average of the reductions in HC, CO and NO_x. These weighting factors, while estimated empirically, still involve a subjective judgement of a number of external factors. Because of the relationship between these weighting factors and the figure of merit, program effectiveness is, in turn, a function of the values of these factors. By parametrically varying these values, one can determine the sensitivity of program selection to weighting factor data employed.

4.3.4 Regional Evaluation

The above examples imply a micro sensitivity analysis, i.e., examination of the relationship between procedure selection and variation in a particular dimension of the model. Macro sensitivity analysis is also possible and regional evaluation can be viewed as such a process. Here, the concern is with the impact of changes in sets of components on the selection of the best inspection/maintenance procedure. Each component set - weighting factors, cost factors, population characteristics, - serves to define a specific air quality region and to distinguish it from all others. By changing these micro component sets, one can establish the macro sensitivity of policy selection to regional variations.

APPENDIX A
STUDY GROUND RULES AND ASSUMPTIONS

Presented herein is a summary of the study ground rules and assumptions expressed or implied in this report.

- 1) All mass and mode emission levels and reduction percentages are reported in terms of an average value for the entire vehicle population.
- 2) The effect of vehicles entering and leaving the population because of attrition and new production are considered. However, all new production vehicles are assumed to have the same parameter, mass, and mode emission characteristics as 1971, NO_x controlled vehicles.
- 3) Emission mean values for vehicle population treated by both the engine parameter and emission inspection procedures vary with time (deterioration) and with the extent of maintenance.
- 4) Basic maintenance of those normally adjusted engine parameters not covered in the enforced maintenance procedure is assumed to be performed voluntarily by the vehicle owner.
- 5) All mandatory maintenance is performed in franchised garages. Mandatory maintenance is limited to restoring the engine parameter listed in Table 2-1 to manufacturer's specification.
- 6) Inspection procedures requiring large capital expenditures (i.e., the purchase of equipment for either remote sensing or exhaust emission measurements) are always performed within a state operated system.

- 7) All vehicles failing a state inspection are reinspected by the maintenance organization, only those engine parameters actually failed are maintained.
- 8) Pass/fail inspection criteria are optimized for the first inspection interval and remain invariant with time.
- 9) The basic cost of maintenance labor and parts is estimated using Chilton's Labor Guide [2]. The actual average invoice cost is estimated by applying an overcharge factor representing unnecessary repair.
- 10) Estimated mean emissions reduction are based on measurements made with the 1972 Federal Test Procedure.
- 11) The parameter deterioration rates and influence coefficients are assumed to be invariant throughout the country. The initial engine maintenance state is determined by the Detroit and Los Angeles parameter field evaluations.
- 12) User inconvenience costs are applied only to those vehicles passing the initial inspection. The resulting maintenance action is not assumed to be an inconvenience since it is in compliance with the law.
- 13) The potential positive benefits of maintenance in terms of improved fuel economy or operating reliability are not reflected in the cost-effectiveness analysis.
- 14) After the first inspection interval (where major malfunctions are repaired), engine parameter malfunctions are assumed to be randomly distributed and therefore, statistically independent of each other.
- 15) The effectiveness of voluntary maintenance is assumed constant throughout the country.
- 16) The training costs incurred in setting up the initial state lane program are incorporated into the program's figure-of-merit.

- 17) Only those parameters which yield cost-effective results are utilized in the specific application.
- 18) The effectiveness of repair is determined from data developed in the garage survey experiment.
- 19) The parameter deterioration and influence coefficient for all three control types is assumed to be linear and constant for each inspection period.
- 20) Estimates for the statistically significant emission reduction are made using the variance developed from the fleet deterioration program.
- 21) All maintenance effects are applied at the end of the inspection interval.
- 22) An estimate of the achieved reduction for the year is based on one-half of the total reduced computed at the end.
- 23) Presently, no difference is made between the various vehicle power trains.
- 24) The criteria for passing an inspection involves the state of engine parameter and/or mode emissions and not composite mass emission levels.
- 25) Vehicles failing a mandatory inspection program do so because of lack of proper maintenance and not because of inspection errors.
- 26) The basic costs for inspection/maintenance (e.g., hourly rate and parts) are equal throughout the country.

APPENDIX B

MODEL LIMITATIONS

The model, although general in design, does not account for several factors which may influence the outcome of proposed or implemented strategies. The two most significant factors are technological forecasting and allocation of the cost burden. The model presently assumes that no significant technological improvements will occur during the time horizon of the program. The introduction of new control technology in the 1974-1975 period may significantly impact the emission reductions achieved from a given strategy. As previously cited, the model assumes that all vehicles entering the population are characterized by the same emission levels, influence coefficients and deterioration rates than those developed for the post 1970 fleet, i.e., 1971.

Another limitation closely related to this issue involves the uncertainty in estimating the effect of major engine repair on predicted emission reductions. The model computes the amount of emission reduction due to a voluntary program using a fixed level of maintenance. A major tuneup during the life of the program could dramatically alternate the basic state of the vehicle population. The model is also limited in terms of the lack of experimental data beyond 12,000 miles. This problem should improve, however, as more time series experimental data become available.

The question "Who should pay?" represents the other salient issue not considered in the analysis. This particular facet of the program has been omitted since it does not directly impact the effectiveness of candidate procedures. Several options are available for cost sharing the operation of a mandatory program of vehicle inspection/maintenance. They included:

- User charge
- DMV general fund
- Vehicle manufacture warranty program
- Federal revenue sharing.

Each of these alternatives goes beyond the problem of capital investment financing for a stateline system (see Section 3.3). The merits and disadvantages of each must be examined in detail before a specific approach could be identified. Furthermore, the selection of an optimal policy may differ depending on the characteristics of the region under examination.

APPENDIX C

INPUT/OUTPUT FEATURES OF THE ECONOMIC EFFECTIVENESS COMPUTER MODEL

C.1 INTRODUCTION

Presented herein is a descriptive narrative on the salient input/output features of the Economic Effectiveness Computer Model. The model's input/output system has been designed to accommodate a wide range of inspection/maintenance options. Basically, the input options can be partitioned into three categories -- inspection procedure, maintenance treatment and geographical area.

The inspection procedure refers to the type and kind of diagnostic evaluation undertaken prior to corrective maintenance. Presently, two basic types of inspection strategies are available:

- (1) Engine Parameter Inspection
- (2) Exhaust Emission Inspection

Within each of these two approaches lies a number of different kinds of inspection alternatives (e.g., idle). Based on a specific inspection strategy, the model determines the optimum pass/fail criteria for the various engine parameters and/or exhaust mode emissions.

Associated with each inspection alternative is a specific maintenance treatment. Mandatory engine maintenance consists of adjusting, repairing or replacing engine parameters which will yield the most cost effective emission reductions for a given air quality region. The model assumes

that all corrective maintenance takes place in a franchised garage and is subject to existing maintenance reliability.

In addition to the various procedural options, the model requires descriptive information on the demographic and air quality characteristics of the candidate metropolitan area. The essential regional components include: (1) vehicle population distributions, (2) vehicle emission levels and engine state, and (3) a quantitative estimate on existing air quality. The last one is used in developing the emission species weighting function.

The computer program which embodies the Economic Effectiveness Model has been coded in FORTRAN IV and is currently operating on a CDC 6400-6500 computer system. Due to its design, it can process a number of potential strategies with little or no change to the model framework or data bank. Simplicity and flexibility characterize the salient features of the input system.

C.2 INPUT OPTIONS

Table C-1 summarizes the current inspection/maintenance procedure options in the Economic Effectiveness Computer Model. The model partitions the engine block components into three major subsystems -- idle, ignition and induction. Associated with each subsystem and inspection technique (either direct or indirect) is a specific maintenance treatment. For example, the maintenance treatment for the idle subsystem consists of adjusting idle air/fuel, rpm, and timing. The model permits the combination of the various subsystems into more extensive inspection/maintenance procedures. The two most logical extensions to the idle program are:

- (1) Idle adjustment with an ignition tuneup (Extensive A)
- (2) Idle adjustment with an ignition and induction tuneup (Extensive B)

Both of these alternatives tend to yield greater emission reductions for higher program costs. Obviously, other combinations of these subsystems are also possible, however, past analysis has shown them to be less attractive.

One of the key variables affecting the cost effectiveness of these alternatives is the inspection pass/fail criteria. Two methods are available for selecting values of inspection criteria for use in Economic Effectiveness Model. One way involves the use of the model's linear programming algorithm. Here, a set of optimal pass/fail criteria for either the parameter and/or exhaust emission inspection are developed for direct incorporation into the model. The other method consists of prescribing a set of desired rejection rates over the time horizon of the

TABLE C-1 INSPECTION MAINTENANCE PROCEDURE OPTIONS

Engine Subsystem	Inspection Approach		Maintenance Treatment
	Parameter	Mode Emission*	
IDLE:			
Fuel/Air RPM Timing	Idle CO Tachometer Timing Light	Idle CO Idle HC Idle HC	Set rich F/A to spec Set slow RPM to spec Set advance to spec
IGNITION:			
Misfire NO _x Control	Idle HC/Cruise 45 HC Vacuum Gage (Dynamometer)	Idle HC -	Replace plugs, points, & condenser Repair or replace
INDUCTION:			
Air Pump PCV Air Cleaner Vacuum Kick Heat Riser	Visual Pressure Gage Blockage Meter Mechanical Gage Visual	- Cruise 45 CO Cruise 45 CO - -	Repair or replace Clean or replace Replace Set rich to spec Free

* Idle and Cruise 45 NO_x emission measurements are also available.

program. Given these values, the model will compute the corresponding pass/fail criteria.

In addition to selecting the desired inspection/maintenance procedure, the model also requires the identification of the candidate regional area. Table C-2 presents the currently available regional options along with a specification of the necessary regional input data. To date, detailed vehicular demographic and emissions data has been collected for only Los Angeles and Detroit. The data for the remaining areas is derived from existing Los Angeles accounts. The singularly most important and controversial regional input factor involves the emission species weighting function. This function permits the combination of the three emission species (HC, CO and NO_x) into a composite numeration which can be used directly in the program's figure of merit. Estimates of this function are normally derived from existing regional air quality conditions.

The Economic Effectiveness Model can also be used to determine the optimal design and configuration of a state lane inspection system. Here, the number and size of station sites can be traded off to ascertain the optimal system mix. Table C-3 delineates the major operational and design variables which not only influence the system configuration but also overall program effectiveness. Nominally, the operational variables can vary with time whereas the design variables, once they have been determined, remain invariant. Inspection time and maintenance reliability have been classified as operational variables since the ruling technology governing their performance will be changing over the course of the program.

Table C-4 presents a schematic overview of the aforementioned input options and data requirements utilized in the Economic Effectiveness Model.

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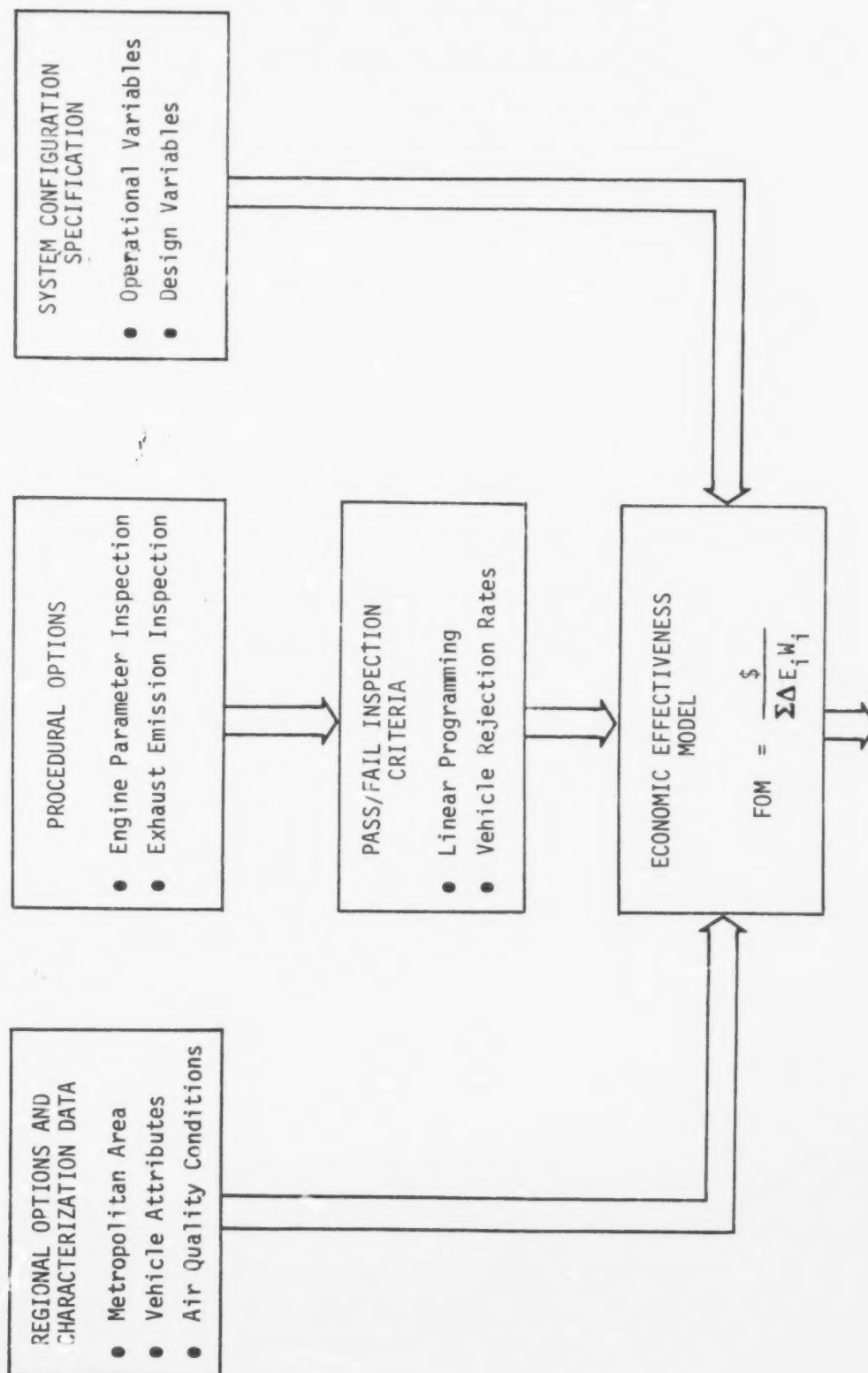
TABLE C-2 REGIONAL OPTIONS AND DATA REQUIREMENTS

<u>Metropolitan Areas</u>	<u>Vehicle Control Types</u>
• Los Angeles Basin • Denver • Detroit • New York • Washington D.C.	• Precontrolled • Controlled 1966-1970 • Controlled Post 1970
<u>Vehicular Attributes</u>	<u>Air Quality Specifications</u>
• Power Train and Population Distributions • Attrition and Growth Rates • Mass Emission Levels • Parameter and Mode Emission Distributions	• Emission Reduction Goals • Emission Species Weighting Factors

TABLE C-3 SYSTEM OPERATIONAL AND DESIGN VARIABLES

<u>Operational Variables</u>	<u>Design Variables</u>
• Inspection Pass/Fail Criteria • Engine Parameters • Exhaust Mode Emissions • Inspection Time • Maintenance Reliability	• Program Horizon • Inspection Period • Inspection System Configuration • Inspection Equipment Specification • Information Processing System • Inspection Training Procedures • User Inconvenience • Program Financial Structure

Table C-4 Flow Schematic of Input Options and Data Requirements



This input system, when combined with the model, constitutes the Economic Effectiveness Computer Processor.

As an illustration of the input system, consider the data given in Table C-5. For ease of implementation, the input system has been divided into two components. The first one specifies, in a literal fashion, the basic procedural options associated with the inspection/maintenance process. For example, in executing an engine parameter extensive B analysis the input system requires the following "key words": parameter, idle, ignition, and induction. Input descriptors are also necessary in identifying the candidate urban area and the composition of the vehicle population to be used in the analysis. In this illustration, the input includes all three control groups (uncontrol, control, and post 70).

In addition to these mnemonic descriptors, the input system also contains a namelist routine. This routine permits one to input directly values of selected operational variables. A partial listing of the namelist variables is presented in Table C-5. Depending on the application, the pass/fail criteria can be either inputted directly or computed from the linear programming algorithm. The XCUT vector specifies the pass/fail criteria for each of the ten parameters for each control fleet. The SXCUT vector yields for each control fleet the pass/fail criteria for the six mode emissions. The remaining namelist variables not listed herein are primarily sensitivity variables. These include the extent of voluntary maintenance and parameter deterioration rates. Ordinarily, these internal variables do not change during the course of the procedure evaluation.

The bulk of the input data is normally invariant (e.g., influence coefficients) and accordingly resides within the Economic Effectiveness Model. This mechanism greatly simplifies the task of executing multiple computer runs and minimizes potential sources of error. A complete listing of all initial data is available through the use of the DEBUG option. A discussion highlighting the relevant output capabilities of the program is given in the following section.

TABLE C-5 REQUIRED INPUT FOR AN ENGINE
PARAMETER EXTENSION/ B INSPECTION/
MAINTENANCE PROCEDURE

<u>Input Descriptors</u>	<u>Definition</u>
Parameter	Identifies engine parameter inspection
Idle	Identifies idle maintenance
Ignition	Identifies ignition maintenance
Induction	Identifies induction maintenance
Loaded	Misfire measured under load
LA	Los Angeles Basin
Uncontrol	Included Pre-1966 vehicles in population
Control	Included 1966-1970 vehicles in population
Post 70	Included post-1970 vehicles in population
<u>Naamelist Input</u>	
HORZIN	Program duration
LPICK = NO	Linear programming option
NPICK = YES	Statistical analysis option
SXCUT	Mode emission pass/fail criteria (optional)
TDIST	Parameter selection vector
TINT	Inspection interval
XCUT	Parameter pass/fail criteria (optional)

C.3 OUTPUT CAPABILITIES AND OPTIONS

The computer program has been designed to provide a wealth of information on the emission reductions capability and associated costs of each inspection/maintenance policy. Table C-6 exhibits a printout summary of model generated data. This printout features several figure-of-merit estimates, the computed emission reductions by species, and a variety of accounting costs.

The program also generates the following ancillary information:

- 1) Mass emission time histories.
 - Aggregated
 - Control type
 - Power train
- 2) Vehicle population distributions and attrition rates over time.
- 3) Summary of input data.
- 4) Engine parameter and mode emission distribution plots and statistics.
- 5) Pass/fail criteria and vehicle rejection probabilities by year.
- 6) Engine parameter rejection rates and average parameter adjustments.
- 7) Summary of regional and operational design results.
- 8) Statistical confidence limits on predicted emission reductions.

A debug option has been incorporated into the major system routine to assist in interpreting program output and in checking out new policy alternatives. This option yields a complete diagnostic analysis on all fundamental calculations within the model.

TABLE C-6 ECONOMIC EFFECTIVENESS SUMMARY PRINTOUT

 * IRM INSPECTION/MAINTENANCE *
 * SYSTEM MODEL *

SUMMARY INFORMATION

ENGINE PARAMETER STRATEGY EXTENSIVE B
 INSPECTION PERIOD IS 12.0 MONTHS

PAYOFF FUNCTION UNADJUSTED (DOLLARS/WEIGHTED EMISSION)	2462.80
PAYOFF FUNCTION STATISTICALLY ADJUSTED (DOLLARS/WEIGHTED EMISSION)	1466.52
PAYOFF FUNCTION AT END OF LAST YEAR (DOLLARS/WEIGHTED EMISSION)	852.85
FC EMISSION REDUCTION (PERCENT)	11.31
CO EMISSION REDUCTION (PERCENT)	4.40
NO EMISSION REDUCTION (PERCENT)	-0.92
HC AVERAGE EMISSIONS (TONS/DAY)	713.81
CO AVERAGE EMISSIONS (TONS/DAY)	5451.44
NO AVERAGE EMISSIONS (TONS/DAY)	541.34
TOTAL COSTS FOR MANDATORY PROGRAM (DOLLARS/YEAR)	125114262.75
TOTAL COSTS FOR VOLUNTARY PROGRAM (DOLLARS/YEAR)	172450530.25
RATIO OF MANDATORY TO VOLUNTARY COSTS (PERCENT)	72.53
INSPECTION CAPITAL COSTS (DOLLARS/STATION)	6.00
AVERAGE INSPECTION OPERATING COSTS (DOLLARS/YEAR)	50160955.13
MAINTENANCE CAPITAL COSTS (DOLLARS)	0.00
AVERAGE MAINTENANCE OPERATING COSTS (DOLLARS/YEAR)	74533277.62
USER COSTS (DOLLARS/CAR)	1.61
COST PER INSPECTION	28.60
COST PER VEHICLE MAINTAINED	23.07
AVERAGE NUMBER OF CARS INSPECTED/YEAR	4374727.51
AVERAGE NUMBER OF CARS REJECTED/YEAR	3468742.77
AVERAGE NUMBER OF CARS MAINTAINED/YEAR	3468742.77
AVERAGE FAILURE PERCENTAGE	.79
TOTAL PROGRAM DURATION (YEARS)	5.00

APPENDIX D

ANCILLARY MODEL DATA

The ancillary model data presented herein is incorporated in the Economic Effectiveness Model. The data has been derived from sources other than the experimental emission program. This data is used mainly in characterizing the economical and operational elements of the model. The data derived from the Emission Test Program is available in Volumes IV, V, and VI.

The average annual parameter adjustments due to voluntary maintenance are depicted in Table D-1. These voluntary maintenance adjustments were formulated from the Air Resources Board surveillance data.

Tables D-2 and D-3 present inspection/maintenance and miscellaneous costs used in the economic analysis model. The times and parts costs were developed from both the experimental programs and Chilton's Labor Guide [2]. As can be seen, the replacement parameters are the most costly and consequently must yield larger emission reductions in order to be competitive with the adjustment parameters, e.g., Idle RPM.

TABLE D-1 EFFECTIVENESS OF VOLUNTARY MAINTENANCE

PARAMETER	AVERAGE ANNUAL PARAMETER ADJUSTMENTS DUE TO VOLUNTARY MAINTENANCE		
	PRE-CONTROLLED	CONTROLLED	POST 1970
Idle CO* ($\pm 1\%$)	0.3	0.4	0.5
Idle RPM* (± 50 RPM)	25.	30.	35.
Timing* (± 2 degrees)	1.5	1.5	1.5
Misfire (Wires & Plugs)	0.07	0.06	0.05
NO _x Device	0.	0.	0.1
Air Pump	0.	0.	0.
PCV	0.1	0.1	0.1
Air Cleaner	10.	15.	20.
Choke Vacuum Kick* (± 0.001 inches)	0.	0.	0.
Choke Heat Riser	0.	0.	0.

*Parameter settings returned to manufacturers' specification

TABLE D-2 INSPECTION/MAINTENANCE COST COMPONENTS

<u>ENGINE PARAMETER</u>	<u>INSPECTION TIMES</u> (Hours)	<u>MAINTENANCE</u>	
		<u>TIMES</u> (Hours)	<u>PARTS</u> (\$)
Idle CO	0.05	0.10	--
Idle RPM	0.05	0.10	--
Timing	0.05	0.10	--
Misfire	0.15	1.0	17.00
NO _x Control	0.10	0.75	20.00
Air Pump	0.25	0.70	47.00
PCV	0.10	0.10	2.00
Air Cleaner	0.05	0.05	5.50
Vacuum Choke Kick	0.10	0.25	--
Choke Heat Riser	0.05	0.25	--
<u>EXHAUST MODE EMISSION (LANE SYSTEM)</u>			
Idle HC		0.025	
Idle CO			
Idle HC + Cruise 45 HC		0.04	
Idle CO + Cruise 45 CO			

TABLE D-3 MISCELLANEOUS DATA

<u>CONSTANT</u>	<u>VALUE</u>
Mechanics Hourly Rate	\$10.00/Hour
Station Attendant Hourly Rate	\$ 3.50/Hour
State Lane Overhead Rate	50 Percent
Information Processing Costs	\$ 1.00/Car
Training Cost	\$500/Man
Discount Rate	7 %/Year
Inconvenience Hourly Rate	\$ 2.00/ Hour
Average Equipment Costs	\$20,000/Station
Station Size	600 Sq. Ft.
Facilities Land Costs	\$ 2.00/Sq. Ft.
Facilities Construction Costs	\$10.00/Sq. Ft.
Emission Weighting Factors (L.A. Basin)	
HC	0.6
CO	0.1
NO	0.3

REFERENCES

1. "The Economic Effectiveness of Mandatory Engine Maintenance for Reducing Vehicle Exhaust Emissions," Vol. III, "Procedures Development," TRW Systems Report in Support of CRC APRAC Project No. CAPE-13-68, 1971.
2. Chilton's Labor Guide and Parts Manual, Motor Age, 40th Edition, 1969.